



# CHICAGO AIR POLLUTION SYSTEM MODEL

**ARGONNE NATIONAL LABORATORY**  
CHICAGO DEPARTMENT OF AIR POLLUTION CONTROL  
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Printed in the United States of America

Available from

Clearinghouse for Federal Scientific and Technical Information

National Bureau of Standards, U. S. Department of Commerce

Springfield, Virginia 22151

Price: Printed Copy \$3.00; Microfiche \$0.65

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City of Chicago

Air Pollution System Model

ARGONNE NATIONAL LABORATORY  
CHICAGO DEPARTMENT OF AIR POLLUTION CONTROL  
DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE  
National Center for Air Pollution Control

Second Quarterly Progress Report

May 1968

by

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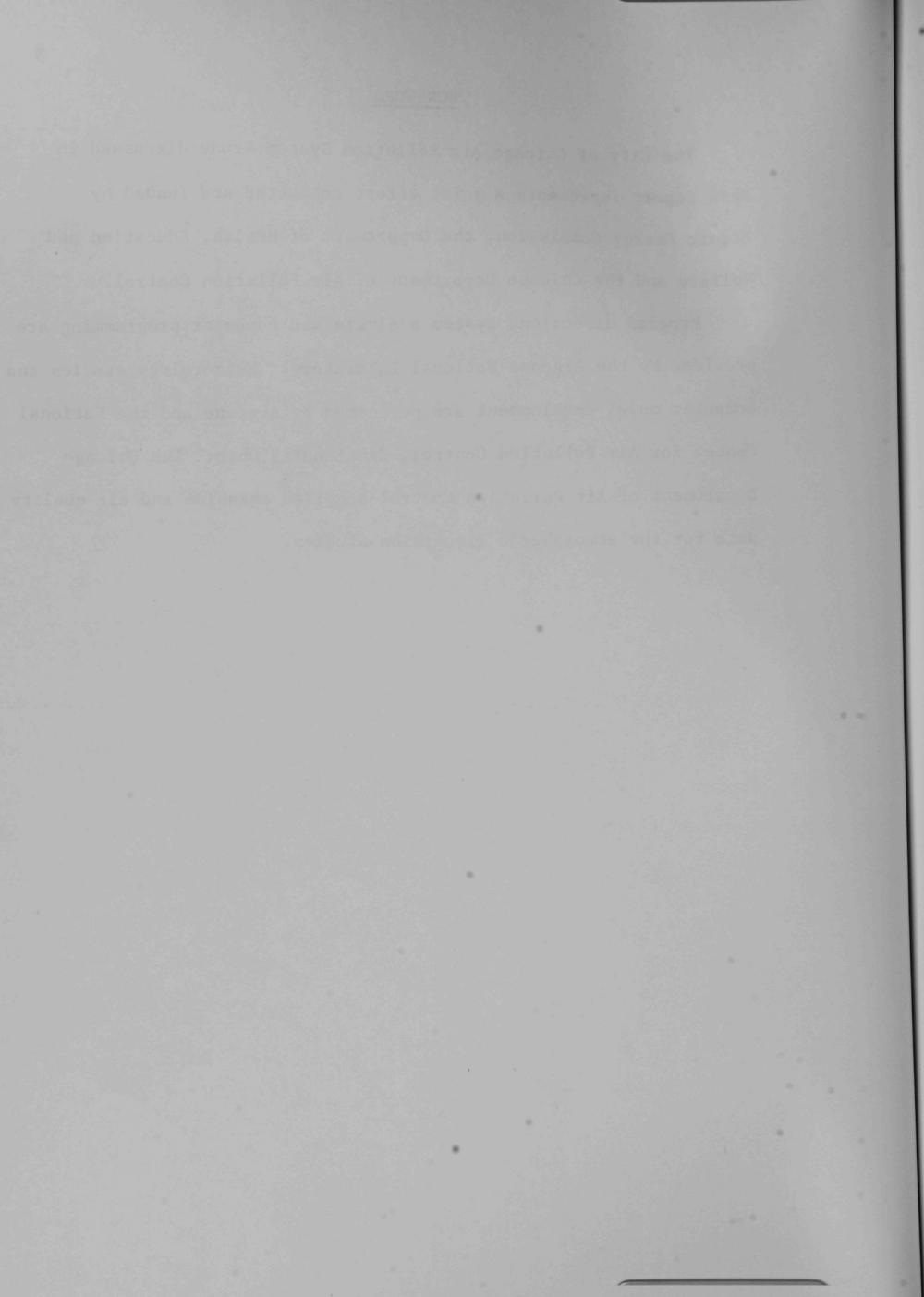
ENVIRONMENTAL SCIENCES



FOREWORD

The City of Chicago Air Pollution System Study discussed in this report represents a joint effort conducted and funded by Atomic Energy Commission, the Department of Health, Education and Welfare and the Chicago Department of Air Pollution Control.

Program direction, system analysis and computer programming are provided by the Argonne National Laboratory. Meteorology studies and computer model development are performed by Argonne and the National Center for Air Pollution Control, Cincinnati, Ohio. The Chicago Department of Air Pollution Control supplies emission and air quality data for the atmospheric dispersion studies.



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## CHICAGO AIR POLLUTION DISPERSION MODEL

### 1.0 Introduction

E. Croke

## 1.0 Introduction

The first quarter of the Chicago Air Pollution System Analysis Program was largely devoted to a survey of the state-of-the-art of atmospheric dispersion model development, to the definition and scoping of the tasks associated with the construction of a computerized, SO<sub>2</sub> dispersion model and to the organization and initiation of the data acquisition effort and scientific studies required to develop a pilot version of this model.

The dispersion model development program that resulted from these initial planning efforts is divided into four major functional areas. These are:

1. Diffusion Analysis
2. Meteorological Studies
3. Emission Inventory
4. Applied Computer Programming

The most significant single milestone achieved during the first quarter of the program was the development of an approach to the construction of an empirical, statistical dispersion model rather than a physical, deterministic prediction system of the kind hitherto attempted for other major cities. Although the development of a statistical model was established as the mainstream effort of the program, a backup study designed to refine an existing physical dispersion model, originally devised for St. Louis, Missouri, was also undertaken.

Studies of Chicago Air Pollution Meteorology were initiated during this period, and several experimental programs were designed by the Argonne

meteorological staff. A major effort to develop an hourly  $\text{SO}_2$  emission inventory for Chicago was also undertaken as a joint project by Argonne and the Chicago Department of Air Pollution Control.

In addition, an operations research analysis directed toward the development of economic, air pollution abatement strategies was initiated, and a preliminary, linear programming methodology for the creation of optimal,  $\text{SO}_2$  emission control plans was devised.

The objectives defined, methods developed and progress achieved during this initial period are discussed in detail in the first quarterly progress report (ANL/ECC-001). That report provides an overall perspective of the dispersion modeling effort as it is viewed by the participating agencies and describes the general plan for this first phase of the total Chicago air pollution system analysis program.

Primary emphasis during the second quarter of the program was placed upon the acquisition of air quality, meteorological and emission inventory data; and on the development of computational tools and analytical methods required to process, store, retrieve and analyze this data.

During this period, the most significant program milestone that was achieved was the completion of the air pollution master information system - a set of linked computer programs designed to prepare and merge data files, to search out and retrieve information from these files, to perform statistical analyses and to display the results of computational studies and data surveys. This system is the basic tool required for the construction of the statistical  $\text{SO}_2$  dispersion model.

In addition to the development of the master information system, a number of other significant milestones were achieved during this quarter in the diffusion analysis, meteorology, emission inventory and optimal abatement strategy phases of the program. These include: a statistical study of the Hyde Park telemetry station air quality data; the completion of the St. Louis physical model development; the definition of preliminary meteorological, air pollution regime criteria; the acquisition, analysis and processing of a major segment of Chicago's power plant and industrial emission data and the construction of an air pollution incident simulation code for the optimal abatement strategy study. Details of these and other studies conducted in support of the Chicago air pollution system analysis effort are discussed in the following sections of this report.

## CHICAGO AIR POLLUTION DISPERSION MODEL

### 2.0 Diffusion Analysis

J. Roberts

E. Croke

D. B. Turner

## 2.0 Diffusion Analysis

### 2.1 General Discussion

The primary objective of the diffusion analysis studies conducted during the first phases of the dispersion model development is to test the effectiveness of the statistical analysis technique proposed for the generation of source-receptor coupling coefficients for each of the eight Chicago telemetered air monitoring (TAM) stations. As described in reference (1), this trial of the statistical approach will be conducted in the form of a pilot study of the Hyde Park TAM station and the aggregate of SO<sub>2</sub> emitters in its vicinity which are considered to be most likely to be "visible" as discrete sources against the general background of the city. The tentative identification of these significant sources was accomplished through the application of a "conventional" gaussian smoke plume dispersion equation using the same atmospheric stability parameters employed by Turner<sup>(2)</sup>.

In order to implement the proposed pilot study, it was necessary to

- 1) Develop the air pollution master information system (see section 5 of this report).
- 2) Accumulate and process meteorological data from the major Chicago airport weather stations and the DAPC meteorological data acquisition network.
- 3) Process and debug the DAPC TAM data tapes in order to develop an hourly average SO<sub>2</sub> and wind vector data file.
- 4) Acquire and process hourly average SO<sub>2</sub> emission data for the twelve "significant" industrial plants and three Commonwealth Edison power stations in the Hyde Park "sphere of influence."

- 5) Conduct statistical and experimental studies of space heating fuel use patterns for commercial and residential high sulfur fuel users on the Hyde Park area.

At the time that this report was prepared, all of these tasks were well underway and, as described in subsequent sections of this report, several are virtually completed. In brief, the status of these efforts is as follows:

- 1) The master information system has been developed.
- 2) Meteorological data from the Midway, Meigs-lakefront, O'Hare and Glenview airports have been acquired. Rawinsonde data from the Peoria, Illinois and Greenbay, Wisconsin stations have also been obtained, as has pyranometer and hygrothermograph data from the Chicago network.
- 3) An extensive TAM data sorting and debugging process is essentially complete. Preliminary one hour, six hour and twelve hour average TAM ( $\text{SO}_2$  and wind vector) data files have been prepared and a final TAM file is in preparation.
- 4) Fuel consumption data for thirty industrial plants and four Edison stations has been acquired. Five industrial plants and three Edison stations have been fully processed.
- 5) Statistical studies of daily commercial and residential fuel use patterns have been essentially completed, and a study of hourly fuel use patterns is in progress. An experimental, building instrumentation program was initiated, but has not yet yielded a body of useful data. Fuel use data for twelve major residential

and six major commercial high sulfur fuel users was acquired in support of the statistical, space heating studies.

Nearly all of the components required for the implementation of the Hyde Park pilot study are available, and preparatory shakedown trials of the master information system have been initiated. It is expected that the first phases of the pilot study will begin shortly, using the inventory of data that is currently incorporated in the master information system.

Concurrent with the preparations required for the initiation of the Hyde Park study, a number of peripheral tasks have been completed. These include:

- 1) A statistical study of data from the Hyde Park TAM station, using the technique of multiple discriminant analysis.
- 2) The completion of the effort to refine the St. Louis physical dispersion model.
- 3) The development of an objective wind vector plotting computer code for the Chicago TAM network.
- 4) An analysis and evaluation of the stack height ordinances employed by the City of Chicago.
- 5) The development of an air pollution incident simulation computer code using a Davidson-type kernel. (Discussed in section 6.0 of this report).

## 2.2 Statistical Discriminant Analyses

### 2.2.1 Discussion

The air pollution regime identification studies described in section 3.0 of this report are directed toward the development of combinations of "standard" meteorological parameters which can be expected to characterize the capability of the urban atmosphere to transport and dilute  $\text{SO}_2$  emissions at any given time. For the initial stages of this effort, certain basic combinations of meteorological parameters - not unlike Turner's "Objective Stability Criteria"<sup>(2)</sup> - have been proposed for the shakedown trials of the master computer program used to develop statistical coupling coefficients between  $\text{SO}_2$  sources and TAM receptors; but these initial criteria are quite general in nature and reflect none of the unique aspects of Chicago's micrometeorology. Neither were they determined, in any quantitative sense, by the actual body of historical, meteorological data which is available for Metropolitan Chicago. The use of "objective stability criteria" in the classical sense of the term is questionable because, no matter how narrow or wide the bandwidths assigned to the predictor variables may be, the combination of predictors which supposedly characterizes a given meteorological regime is actually associated with a very large number of probabilistic states of the atmosphere, of which only one will be realized in fact. To apply "objective stability criteria," therefore, without knowledge of the probability distribution of the possible stability states that are associated with a given set of criteria is, in effect, a classification process for which no quantitative or historical justification exists. It is fairly safe to apply such intuitive criteria in very gross classification schemes, i.e., cloudy vs.

clear weather or precipitation vs. no precipitation situations; but to refine the stability regime classification criteria beyond this level, to identify the variables which establish a given stability regime in the order of their significance and to reflect the unique aspects of the micrometeorology of a given urban area requires that the meteorological data inventory for the area in question be analyzed and employed in the construction of an empirical, probabilistic regime classification scheme. If this classification scheme must be used as part of a digital computer prediction system, then it is also necessary that the classification method be quantitative in nature.

One approach to the development of a probabilistic classification scheme for meteorological regimes is to employ the method of multiple linear regression analysis to derive values for some continuous variable or combination of variables which is presumed to characterize atmospheric stability. "Standard" meteorological parameters would be the independent variables in the linear equations so derived. One of the major advantages of such an approach is that it provides the meteorologist with a way to cope with the enormous inventory of data at his disposal by allowing him to take advantage of digital computer techniques in performing his analyses. Such a statistical approach is, in fact, not greatly different from that currently proposed for the development of source-receptor coupling coefficients by means of the master computer program (section 5.)

On the other hand, Miller<sup>(3)</sup> has noted a fairly serious inadequacy in the assumption that the value of any meteorological parameter could be calculated by a linear regression equation, with the error associated with the prediction being normally distributed about the predicted value.

A case in point is the situation represented by the passage of a cold or warm front. The values predicted for atmospheric stability, temperature, wind velocity, etc. by a conventional linear regression equation which implies a continuous variation of the dependent variable would very probably represent that associated with the shallow transition zone at the leading edge of the front rather than the quasi-steady state values which prevail on either side of the front. Moreover, the superposition of the error distributions associated with either side of the front would further reduce the representativeness and accuracy of the prediction.

What is required for air pollution regime identification, therefore, is a method for statistically predicting the probability that a given, well-defined regime will prevail, rather than a method of evaluating the transition from one regime to another. It appears that the technique of statistical discriminant analyses may provide this capability.

### 2.2.2 Methodology

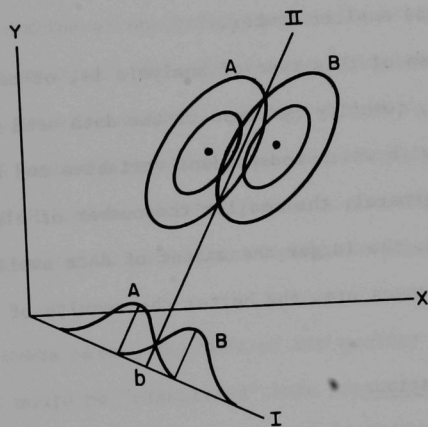
Discriminant analysis<sup>(4,5)</sup> is a statistical technique somewhat akin to linear multiple regression analysis by which observations of some "dependent" variable and the set of "predictor" variables which supposedly determine the value of the dependent variable can be grouped into classes. It is then feasible to determine which of the predictor variables enable the distinctions between classes of the dependent variable to be most clearly made. If several of these predictor variables can be measured for each value of the dependent variable obtained, it may be found that some linear

function of the predictors is more effective in distinguishing groups than is any one of them. If such a linear equation in the predictors can be derived, it can be used with any set of observations of these predictors to compute a "score" which determines in what class the dependent variable which accompanies the observations should belong.

Discriminant analysis may therefore provide a procedure for estimating the position of a given meteorological regime on a line in predictor space which best separates discrete regimes. The estimate is obtained in terms of one or more linear functions of the predictor variables which are associated with the given regime.

Figure 2.1 provides a geometric interpretation of discriminant analysis for a case in which only two groups and two variables are involved<sup>(5)</sup>. The groups A and B are defined by the sets of ellipses which represent the locus of points of equal density for each group. For example, the outer ellipse of group A might contain 90% of all the observations made within group A, etc. The centroid of each group is shown, and ideally, the observations within a group are normally distributed about this centroid.

The points at which corresponding ellipses intersect define a line II. A second line I may be constructed, orthogonal to II, and, if the points in XY space are projected onto this line, the overlap between groups will be smaller than for any other line. An observation which happens to lie on line II has an equal probability of belonging to either group. The point b



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Fig. 2.1 Multiple-Discriminant Analysis

on line I divides the one-dimensional discriminant space into two regions. The discriminant analysis technique, in effect, derives the equation of I and permits an evaluation of the probability that a "score" value computed along I corresponds to group A or group B.

Additional discriminant lines, all mutually orthogonal, may be derived by the same technique in order to "sharpen" the discrimination. The maximum possible number of linear discriminant functions is equal to the number of predictor variables or to one less than the number of groups -- whichever is the smaller number.

The success of this type of analysis is, of course, strongly dependent on the quality, quantity and type of the data used in the analysis and the effectiveness with which independent variables and sets of data are selected. In general, the smaller the number of classes into which the data is divided, the larger the amount of data available and the more discrete the classes are, the better the results of this type of analysis will be.

### 2.2.3 Possible Applications

The use of multiple discriminant analysis as a device for statistically partitioning Chicago's meteorological data inventory into air pollution regime classes is regarded as a very promising approach which will be explored in some detail. Of potentially greater importance is the possibility that this method might prove more efficacious than conventional linear regression analysis in the prediction of  $\text{SO}_2$  concentrations. One important reason for this is the fact that, according to the Central Limit Theorem,

linear functions of variables are more likely to be orthogonal, (i.e. not autocorrelated) than are the variables themselves. Thus, multiple discriminant scores are more likely to satisfy the assumption of a multivariate normal distribution than are the original meteorological variables<sup>(5)</sup>.

A second reason for considering this possibility is the fact that, for the purposes of implementing an air pollution control plan, the DAPC has no reason to be in the least interested in a prediction of the value of the  $\text{SO}_2$  concentration at any point in the city. Rather, that organization requires a predictive scheme for making management decisions regarding whether or not an emission control strategy should be implemented and, if so, what level of controls should be imposed. Thus, the DAPC is likely to be more concerned with the probability that a certain bandwidth or class of  $\text{SO}_2$  concentrations will prevail than with the actual value of the  $\text{SO}_2$  concentration.

In more concrete terms, the body of air quality data accumulated by the Chicago DAPC could be "classified" into appropriate  $\text{SO}_2$  concentration bands such as 0 - 0.2 PPM, 0.2 - 0.4 PPM, 0.4 - 0.6 PPM, >0.6 PPM, etc., and a level of emission control could be defined for each band. Within each of these bands or classes would be an accompanying set of predictor variables such as wind velocity and direction, solar altitude, mixing layer depth, urban lapse rate, etc. By using discriminant analysis techniques on this body of data, linear equations in the predictors could be developed which would yield scores corresponding to the selected bands or classes of  $\text{SO}_2$  concentrations and control plans. Since a

multi-level abatement strategy with strata of control corresponding to the predicted classes of  $\text{SO}_2$  concentrations would seem to be more compatible with the aims and purposes of the DAPC than an air quality prediction scheme per se it would be desirable to render the development of air pollution abatement strategies an integral part of a prediction methodology rather than treat it as a superstructural appendage to a predictor. It appears that the discriminant statistical classification technique might satisfy this requirement. It could be employed to automate a choice between several discrete abatement strategies, and would indicate the probability that the selected strategy would actually be required. The air pollution control engineer could therefore proceed directly from meteorological and emission data to the selection of a level of control with no intervening assessment of the implications of the predicted  $\text{SO}_2$  concentrations - in principle, a considerable improvement in the efficiency and simplicity of an air quality management effort.

Standard discriminant analysis computer codes are available<sup>(6)</sup> at Argonne to generate the required "score" equations for this statistical classification scheme.

#### 2.2.4 A Preliminary Test of Discriminant Analysis

As a preliminary trial of the method of statistical discriminant analysis, the TAM data file was employed to develop a set of six hour average  $\text{SO}_2$  and wind vector values for each of the eight air quality monitoring stations. These averages were developed for the time periods 0900-1500, 1500-2100, 2100-0300 and 0300-0900; thus they

corresponded to the daylight, evening transition, night and morning transition periods.

This subset of the master data file was further partitioned into periods corresponding to the four seasons December-February, March-May, June-August and September-November. This constituted an attempt to artificially sensitize the data to source influences such as space heating emissions and to minimize the effects of variance due to seasonal, climatological phenomena.

Finally, the data for the Hyde Park TAM station was partitioned into two air quality classes:  $\text{SO}_2 \geq 0.2$  PPM and  $\text{SO}_2 \leq 0.2$  PPM -- a fairly high average concentration when assessed over a six hour period. The wind vector data associated with these two classes of  $\text{SO}_2$  concentrations during the daylight hours in the winter season was input to a standard discriminant analysis computer code. In the high  $\text{SO}_2$  concentration group, 61 observations were available from the total TAM data inventory. These spanned a period from January 1966 through February 1967. In the low  $\text{SO}_2$  group for the same period, 87 observations were available -- thus a total of 148 observations were employed for the analysis. No attempt to extract spurious data was made, nor was any sort of selectivity imposed. Neither was any biasing of the data attempted -- aside from the partitioning process already described.

#### Hyde Park Discriminant Analyses - TAM Data Only

The results of the first analysis were quite encouraging -- particularly in view of the fact that the only predictor parameters involved were wind

direction and velocity and considering that some of the observations employed were undoubtedly spurious due to errors in the TAM data.

The mean predictor values and the dispersion matrix for this initial trial analysis are tabulated below.

Mean Predictor Values

	<u>Velocity (k)</u>	<u>Direction (Deg)</u>
SO <sub>2</sub> > 0.2 PPM	8.63	267.7
SO <sub>2</sub> < 0.2 PPM	7.24	154.3

Variance-Convariance Matrix

	<u>Velocity</u>	<u>Direction</u>
Velocity	20.2	193.5
Direction	193.5	7744.0

The computer code automatically rejected wind velocity as a predictor variable since it constituted less than 5% of the value of the derived discriminant score over the given range of predictor values. The selection of the sensitivity required for a variable to qualify as a significant predictor is an input option for the computer code, and the choice of 5% was essentially arbitrary for this trial run.

With wind direction remaining as the only significant prediction variable, the analysis revealed that a fairly sharp discrimination was possible in the high pollution group; that is, the standard deviation of wind directions associated with high SO<sub>2</sub> concentrations was relatively small, while that associated with the low concentrations was considerably

larger. The results are tabulated below:

Two Group Dispersion Matrix

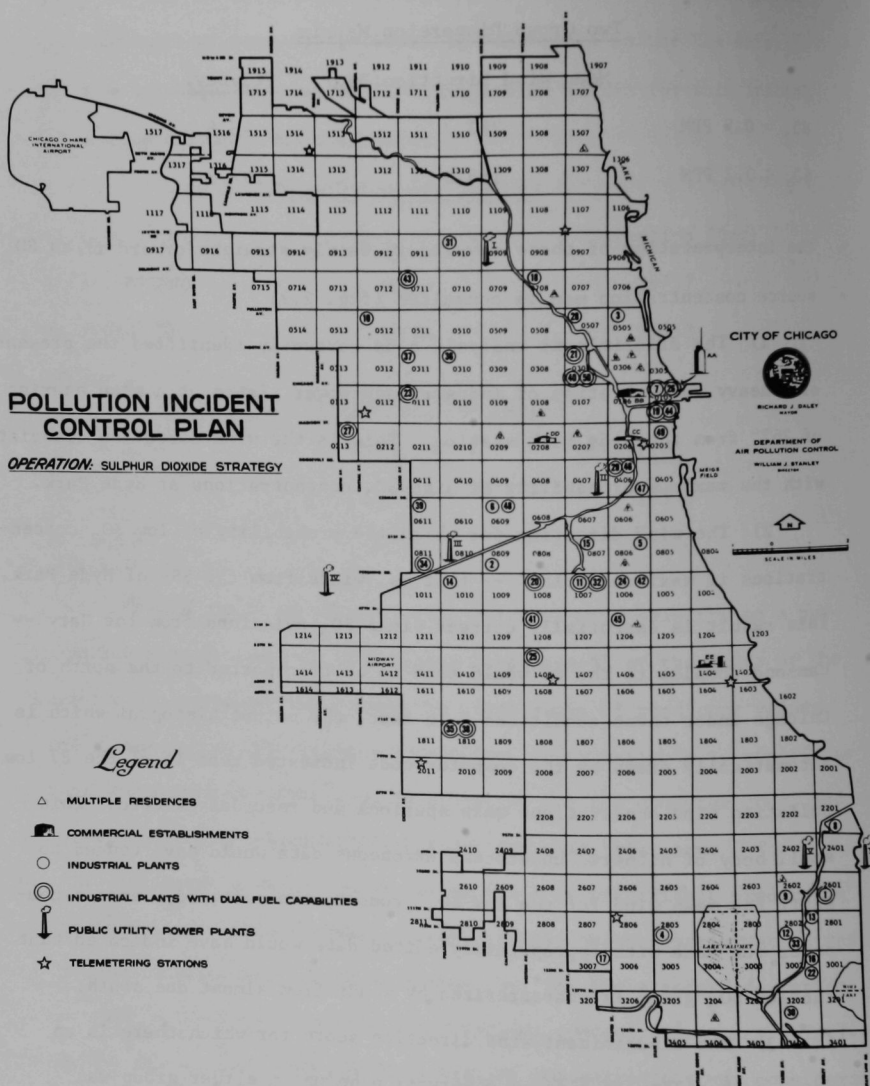
	Mean Wind Direction(Deg)	Std.Dev.
SO <sub>2</sub> > 0.2 PPM	267.7	43.8
SO <sub>2</sub> < 0.2 PPM	154.3	107.5

The interpretation of these results is fairly straightforward if an SO<sub>2</sub> source concentration map is consulted (fig. 2.2).

1) The discriminant analysis code correctly identified the presence of a heavy concentration of industry and power plants at a mean bearing of 267° from the Hyde Park station. This is the wind direction associated with the maximum probability of high SO<sub>2</sub> concentrations at Hyde Park.

2) The wind direction for which the probability of low SO<sub>2</sub> concentrations is maximum is 154° -- that is, winds from the SSE of Hyde Park. This result is essentially correct since SO<sub>2</sub> emissions from the Gary -- Hammond complex to the SE would tend to be transported to the north of Chicago under these conditions. In fact, the output histogram which is automatically drawn by the computer code indicated that 15 of the 87 low pollution wind observations were spurious and recorded as zero. This small body of hitherto undetected erroneous data would have tended to shift the mean wind for the low SO<sub>2</sub> group to the eastward, hence a computer run made with appropriately edited data would have indicated that the low SO<sub>2</sub> group is characterized by winds from almost due south.

3) The discriminant wind direction score for which there is an equal probability of a given observation being in either group was



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Fig. 2.2 Pollution Incident Control Plan Map

established to be  $240^{\circ}$ . Thus, winds from compass points below  $240^{\circ}$  are most likely to accompany low  $\text{SO}_2$  concentrations, while winds above  $240^{\circ}$  will characterize  $\text{SO}_2$  concentrations in excess of 0.2 PPM.

This relatively simple demonstration of discriminant analysis did not of itself reveal a great deal of information that could not be inferred by scrutiny of a source map; however this was due solely to the fact that the only significant discriminant variable that was included happened to be one that lends itself to analysis by visual inspection. It is significant that the results were physically realistic, in that a known industrial concentration was quantitatively identified and the extent of the wind sector which is sensitive to that concentration was defined. The lack of a sharp grouping in the low  $\text{SO}_2$  class indicates the generally uniform distribution of small  $\text{SO}_2$  sources to the south of Hyde Park and the prevalence of a general southwesterly flow in the Chicago area. The rejection of wind velocity as a predictor during winter daylight hours is significant in view of the generally accepted importance of the parameter in air pollution prediction schemes. For Chicago, at least, it appears that the variability of winter daylight wind velocities about a mean value of approximately eight knots is sufficiently small that, for practical purposes, this parameter will not serve as a useful predicting variable. (The advent of a major stagnation during the period analyzed would have had an interesting effect on this result).

### Hyde Park Discriminant Analysis - TAM and Airport Data

In an attempt to sharpen the discrimination achieved in the first trial run, the same body of  $\text{SO}_2$  and wind vector data was merged with degree-day values measured at the local airport (Midway), and the analysis was repeated with this added predictor variable. The mean predictor values and dispersion matrix are shown below:

#### Mean Predictor Values

	<u>Degree Day (°F)</u>	<u>Direction (Deg)</u>	<u>Velocity (k)</u>
$\text{SO}_2 > 0.2 \text{ PPM}$	43.6	267.7	8.63
$\text{SO}_2 < 0.2 \text{ PPM}$	34.2	154.3	7.24

#### Variance - Covariance Matrix

	<u>Degree Day</u>	<u>Direction</u>	<u>Velocity</u>
Degree Day	133.6	43.4	5.54
Direction	43.4	7744.0	193.5
Velocity	5.54	193.5	20.2

A linear discriminant function was generated by the code and was employed, as before, to compute the probability that a given set of observations of the predictor variables would be associated with the high and the low pollution classes. The computer code automatically assigns a given set of observations to one or the other group depending on the results of this probability computation. This procedure is therefore a test of how effectively the linear discriminant function actually works on the predictor variables which were used to derive it.

The resultant classification matrix is shown below:

	<u>Correct</u>	<u>Erroneous</u>	<u>Total</u>
$\text{SO}_2 > 0.2 \text{ PPM}$	53	8	61
$\text{SO}_2 < 0.2 \text{ PPM}$	63	24	87

The derived discriminant function was successful in identifying a member of the high  $\text{SO}_2$  group in 87% of the observations provided for that group and in 72% of the cases provided for the low  $\text{SO}_2$  group. The total score was a fairly impressive 79%, since the function chose correctly 116 out of 148 times. It should be noted that these are not "skill" scores in the strict sense, since no assessment of the probability of making random correct guesses was included. It is also necessary to note that these results are not validated in that the discriminant functions have not been verified with any observation from outside of the body of data used to derive them. It is therefore clear that considerable additional work must be done in order to refine the discriminant analysis technique and to verify the encouraging results obtained from these initial tests; however the method appears to be sufficiently promising for both the meteorology studies and the diffusion analysis effort that it will be further evaluated during the forthcoming months in an attempt to develop it as an effective statistical research tool.

## 2.3 Physical Dispersion Model

### 2.3.1 Background

A dispersion model for transport and dispersion of atmospheric pollutants was developed and tested using a source inventory of sulfur dioxide in the St. Louis-East St. Louis Metropolitan Area and measurements of 24-hour sulfur dioxide concentrations at 40 locations. Two-hour concentration measurements were also made at 10 of these locations. Measurements were available for 89 consecutive days during the period December 1964 through February 1965.

Initial results of comparisons between calculated concentrations and observed concentrations indicated many of the calculated values exceeded observed concentrations. These results (overcalculations, calculated exceeded observed) appeared to be related to the contributions from sources with effective heights above 50 meters. It was thought that this overcalculation was due to too small a value for calculated plume rise for these sources. It was expected that some changes, to improve the model, could be made relatively easily.

### 2.3.2 Tests of Model Changes

A number of changes in the model were made and tested with two days data using the computer facilities at Argonne National Laboratory. One of the best days and one of the worst days, as far as comparison between calculated and observed concentrations was concerned, were chosen to provide a fair evaluation of the effect of the changes. The following nine tests were made:

1. Use additional plume rise (twice that calculated from Holland plume rise equation) for the 22 sources for which plume rise was previously calculated using Holland's equation.
2. Use effective heights higher than 20 meters, for selected area sources to better represent the heights of emission from built up areas of the city. (All 1200 area sources were previously assumed to have an effective height of emission of 20 meters.) This resulted in 121 area sources with effective height 30 m., 5 with 40 m., 1 with 50 m. and the other 1073 remain at 20 m.
3. Calculate plume rise using Holland's equation for an additional 14 point sources even though the information on stack diameter, stack gas velocity, and exit temperature were quite meager.
4. Allow sigmas ( $\sigma_y$  and  $\sigma_z$ ) to vary with effective height of sources for source heights greater than 30 meters. The sigmas vary inversely with the wind speed so that the sigmas decrease with height as the wind speed increases with height.
5. Integrate to determine the concentration at a receptor point from an area source rather than use a virtual time to account for the area source.
6. In addition to integrating for area sources item 5 above, consider a finite size for 10 of the sources previously considered as points.
7. Changes 2 through 6 together.
8. Changes 2 and 4 through 6 and calculate twice Holland's plume rise for all sources for which plume rise is to be calculated, i.e., the 22 stacks for which plume rise was originally calculated, plus the 14 sources added in change 3.

9. Changes 2 and 4 through 6 and three times Holland's plume rise for the 36 sources with plume rise.

#### Production Model

Results of comparisons between calculated concentrations from the above tests and observed concentrations indicated that the following changes could be expected to result in an improved model.

1. Use various area heights (change 2 above).
2. Calculate plume rise for the additional 14 sources (change 3 above).
3. Use twice the plume rise calculated from Holland's equation as an estimate of the effective height of emission for all 36 sources for which plume rise is calculated.

The above three changes were incorporated into the model and production computer runs completed for the 89 days of data. The model calculates concentrations for points at 5,000 foot intervals over a grid 19 x 17 mile for each two hour-period. This is accomplished by calculating a space-time trajectory of the  $\text{SO}_2$  transport and dispersion for each of 62 point sources and one for each 25 of the 1200 area sources for each two-hour period. There are 1200 area sources. The contribution to the concentration at each point from each source is accumulated until all sources have been considered for that 2-hour period. Concentrations at each point in the grid are printed for each 2-hours and concentrations for the 40 station locations for which observed concentrations are available, are interpolated from the grid and both printed in the form of a map and punched on output cards. Travel time from source to receptor is considered to determine in which two-hour period a receptor receives

pollution from a given two-hour emission. For example, if the emission being considered takes place between the hours of 0800 and 1000 and the travel time to a given receptor is 5.5 hours, the period from 1400 to 1600 is when this receptor is affected by the transported pollution. Twenty-four hour concentrations for both the grid and 40 stations are determined by averaging concentrations from 12 two-hour periods.

### 2.3.3 Preliminary Analysis of the Production Model

A contingency table (Table 2.1) has been prepared for the 89 days at 40 stations to compare calculated and observed  $\text{SO}_2$  concentrations for 24 hours. From this table it can be seen that 1160 are in the correct category. The number correct by chance can be calculated from the contingency table. This is 778. The skill score is found from:

$$\begin{aligned}\text{Skill score} &= \frac{\text{correct-chance}}{\text{total-chance}} \\ &= \frac{1160-778}{3341-778} \\ &= 0.15\end{aligned}$$

The skill score indicates that the model exhibits some degree of skill. Note in the contingency table that, although the model underestimates the number of occurrences of concentrations less than  $200 \mu\text{g m}^{-3}$  and overestimates the number over  $200 \mu\text{g m}^{-3}$ , the numbers calculated and observed for the various classes are not greatly different.

Calculated and observed concentrations were compared for both 2-hour and 24-hour periods to determine the percentage of calculated values within various errors of the observed concentrations. Table 2.2 shows the

## 24-hour CALCULATED CONCENTRATION

24-hour OBSERVED CONCENTRATION	0-49	50-99	100-199	200-299	300-399	400-499	≥ 500	TOTALS
	0-49	361	212	132	27		0	740
	50-99	217	241	319	130	36	8	953
	100-199	105	179	425	258	92	33	1104
	200-299	9	40	146	110	67	24	404
	300-399	1	12	33	25	21	4	100
	400-499	1	1	8	10	2	0	24
	500	0	2	5	4	3	0	16
TOTALS	694	687	1068	564	227	71	30	3341

Table 2.1

cumulative percentage of both 24-hour and 2-hour comparisons from extremes of undercalculation to overcalculation. Note that in the case of 24-hour values, 41.0% are undercalculated and 58.4% overcalculated, whereas for 2-hour values, 53.8% are undercalculated and 45.5% overcalculated. It can also be seen that there is a greater number of large errors in the two-hour comparisons. This is due somewhat to the greater range of observed and calculated concentrations over the shorter time period.

Table 2.3 indicates the percentage of calculated concentrations within selected limits of observed concentration. Of the 24-hour data nearly half of the calculated values are with  $\pm 50 \mu\text{g m}^{-3}$  of the observed and nearly 60% are within a factor of 2.

Another way to express results of the model is to compare areas with concentrations exceeding a given value for both calculated and observed. Isolines of concentration (lines of equal concentration) were drawn for calculated 24-hour concentrations based on the computer output for 323 points a (19 x 17 grid). To draw isolines for observed concentrations, only 40 points (the sampling stations) are available. Therefore isolines for observed concentrations are less detailed and also less accurate in position. Although these are not directly comparable due to the number of points upon which the lines are based, the  $200 \mu\text{g m}^{-3}$  line was selected for comparison anyway. Concentrations of this magnitude occur nearly every day for the period under consideration (Dec.-Feb.).

TABLE 2.2

## CUMULATIVE PERCENTAGE

(from undercalculation to overcalculation)

	24-hour (40 stations)	2-hour (10 stations)
Undercalculated by more		
than $200 \mu\text{g m}^{-3}$	1.7%	9.8%
Undercalculated by more		
than $100 \mu\text{g m}^{-3}$	8.0%	20.2%
Undercalculated by more		
than $50 \mu\text{g m}^{-3}$	18.1%	30.2%
Undercalculated	41.0%	53.8%
No error	41.6%	54.5%
Overcalculated		
to $50 \mu\text{g m}^{-3}$	65.9%	70.9%
Overcalculated		
to $100 \mu\text{g m}^{-3}$	80.5%	79.8%
Overcalculated		
to $200 \mu\text{g m}^{-3}$	94.0%	89.8%
Overcalculated		
$\geq 200 \mu\text{g m}^{-3}$	100%	100%

This comparison can be evaluated quantitatively by determining a score called the threat score<sup>(7)</sup> commonly used in evaluating precipitation forecasts. The threat score is:

$$T_s = \frac{A_{com}}{A_{cal} + (A_{obs} - A_{com})}$$

where  $A_{cal}$  is the area within the isopleth of calculated concentrations,  $A_{obs}$  is the area within the isopleth of observed concentration and  $A_{com}$  is the area common to both. This score varies from zero if there is no overlap of areas to 1.0 if the calculated and observed areas are coincident. An example of this type of analysis is shown in Figure 2.3.

for the 24-hour period ending at 1400 on December 10, 1964. Each station location is plotted as an X with the calculated  $SO_2$  concentration above the X and the observed concentration beneath it. The  $200 \mu g m^{-3}$  isopleth of calculated concentration is shown as a dashed line. The  $200 \mu g m^{-3}$  isopleth of observed concentration is shown as a solid line. The area common to both is denoted by diagonal lines across the area. The threat score for this case is 0.46. The threat score is calculated also using 24-hour persistence, i.e., using the observed  $200 \mu g m^{-3}$  isopleth from yesterday as an estimate for today. Table 2.4 shows a comparison of the threat scores for each day for the first 10 days of data. Note that the model gives a better estimate than persistence for 8 of the 10 days and the same as persistence for one other day. Analysis of the output of the St. Louis model will be completed next quarter.

TABLE 2.3.

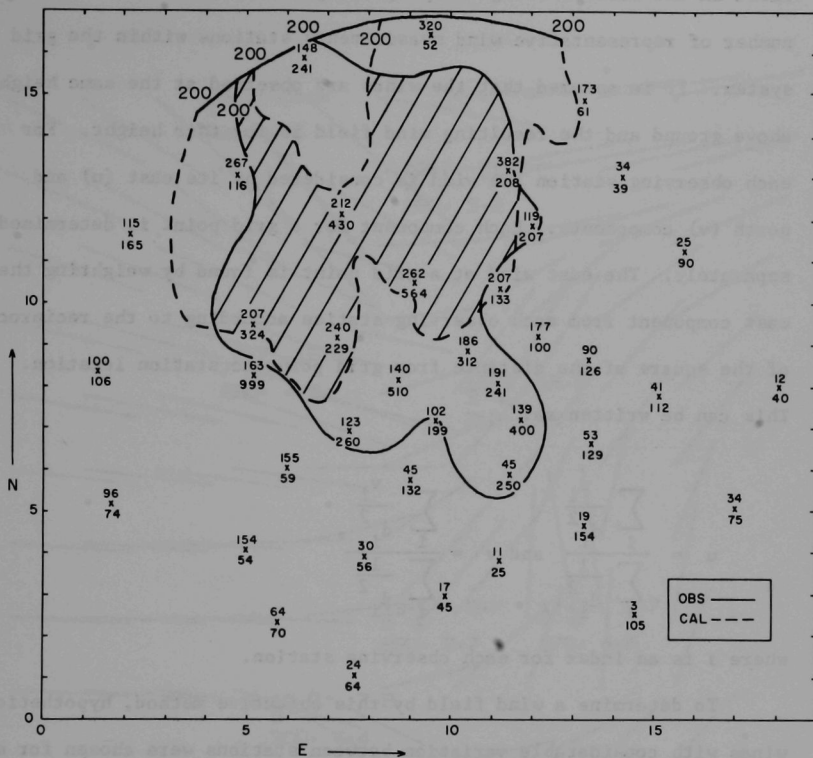
PERCENTAGE OF CALCULATED CONCENTRATIONS WITHIN SELECTED  
LIMITS OF OBSERVED CONCENTRATION

	24-hour	2-hour
No Error	0.6%	0.8%
Within $\pm 10 \mu\text{g m}^{-3}$	12.3%	
20	23.2%	
30	31.9%	$\pm 25 \mu\text{g m}^{-3}$ 26.2%
40	40.4%	
50	47.7%	40.7%
Within $\pm 50\%$	47.0%	38.0%
Within a factor of 2	59.8%	46.7%

TABLE 2.4

THREAT SCORE FOR FIRST TEN DAYS DATA.

<u>Day Number</u>	<u>Date</u>	<u>Threat Score from Calculated Values</u>	<u>Threat Score from Persistence</u>
1	2 December 1964	.28	.42
2	3 December 1964	.34	.03
3	4 December 1964	.22	.20
4	5 December 1964	.09	.09
5	6 December 1964	.47	.15
6	7 December 1964	.39	.12
7	8 December 1964	.37	.31
8	9 December 1964	.23	.13
9	10 December 1964	.46	.25
10	11 December 1964	.11	.09



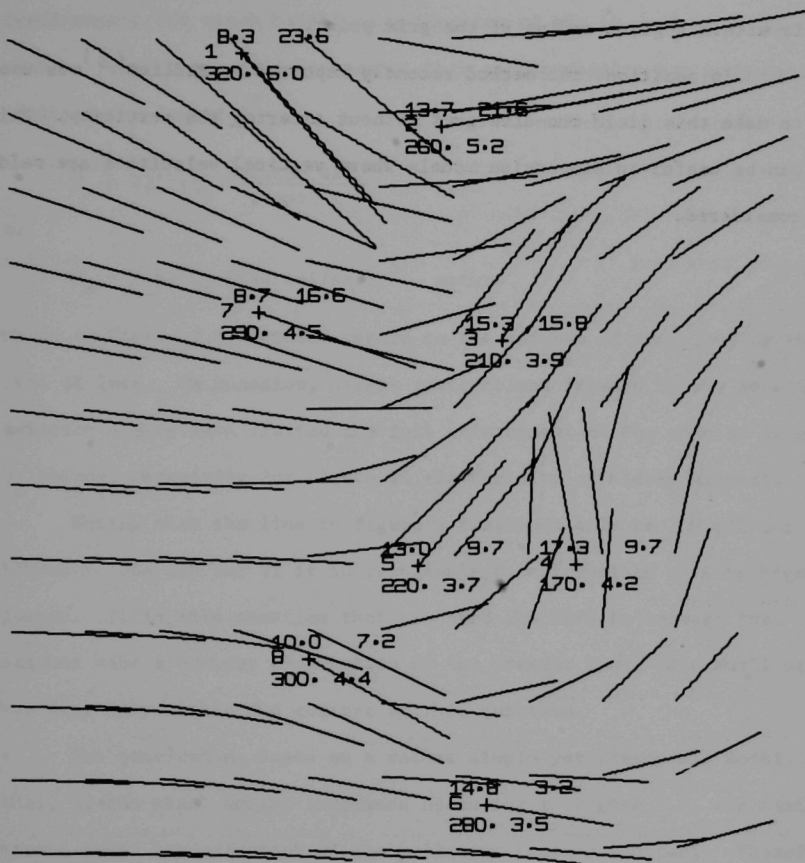
### 2.3.4 Objective Wind Analysis

A method of objective wind analysis was devised so that a wind field in the form of a regularly spaced grid can be obtained from any number of representative wind measurements stations within the grid system. It is assumed that the winds are observed at the same height above ground and the resulting wind field is for this height. For each observing station the wind is considered by its east (u) and north (v) components. Each component for a grid point is determined separately. The east wind at a grid point is found by weighting the east component from each observing station according to the reciprocal of the square of the distance from grid point to station location. This can be written as:

$$u = \frac{\sum_i \frac{u_i}{d_i^2}}{\sum_i \frac{1}{d_i^2}} \quad \text{and} \quad v = \frac{\sum_i \frac{v_i}{d_i^2}}{\sum_i \frac{1}{d_i^2}}$$

where i is an index for each observing station.

To determine a wind field by this objective method, hypothetical winds with considerable variation between stations were chosen for eight stations having the relative positions of the eight telemetered stations of the Department of Air Pollution Control of Chicago. The resulting wind field is shown in Figure 2.4. although only every other wind vector in both the east-west and north-south directions are plotted. The vector emanating from each plus sign is the original wind, its direction (degrees)



112-9718

Fig. 2.4 An Objective Wind Field Derived From Observations at 8 Points. The Plus Sign Indicates Station Location with Station Number to the Left, Original Wind Direction and Speed Beneath and Station Location Above.

and speed ( $\text{m sec}^{-1}$ ) is plotted beneath each station. The station number is plotted to the left and the x, y coordinates plotted above each station. In applying this method to obtain a wind field it may be desirable to include the winds from each station only if the station is within a given radius of the grid point.

In addition, the method recently reported by Endlich<sup>(8)</sup> was used to make this field non-divergent without altering the vorticity. This can be useful to dispersion models where vertical velocities are seldom considered.

## 2.4 Evaluation of the Stack Height Ordinance of the City of Chicago

### 2.4.1 Summary

The Chicago Air Pollution Control Department has purview over the interpretation of that portion of the city building code which sets requirements for stack height as a function of the thermal power of the plant. For the past fifteen years, this responsibility has been met by applying the function<sup>\*</sup>

$$H_s = 18. (Q_p \frac{\text{Million BTU}}{\text{hour}})^{.5} \quad \text{feet}$$

or

(1)

$$H_s = (.65 Q_p \text{ Kilo cal/sec})^{.5} \quad \text{meters}$$

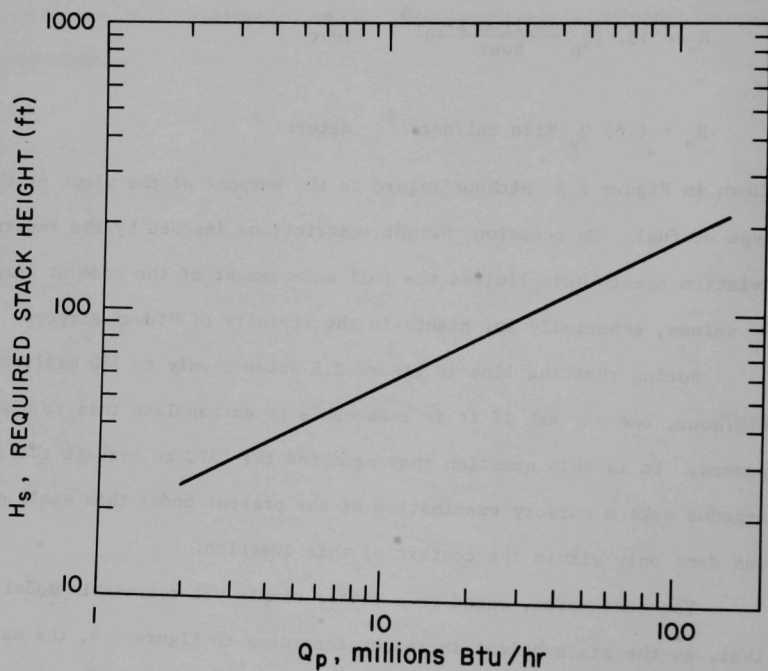
shown in Figure 2.5 without regard to the purpose of the plant or the type of fuel. On occasion, height restrictions imposed by the Federal Aviation Agency have limited the full enforcement of the code at large  $Q_p$  values, especially for plants in the vicinity of Midway Airport.

Noting that the line in Figure 2.5 extends only to 150 million BTU/hour, one may ask if it is reasonable to extrapolate this to higher powers. It is this question that prompted the DAPC to request that Argonne make a cursory examination of the present code; this small study was done only within the context of this question.

The conclusion, based on a rather simple yet reasonable model, is that, as the stack height increases according to Figure 2.5, the maximum ground level concentration of the pollutant remains constant. Therefore, assuming that this criterion is valid, the present curve should be

---

<sup>\*</sup>Nomenclature is listed in Table at end of this section.



112-9719

Fig. 2.5 Stack Height vs. Heat Emission (City of Chicago Ordinance)

extrapolated. However, it should be emphasized that this code in no way considers two very important factors: 1) the nature of the pollutant, e.g., there is no incentive to use less noxious fuels, and 2) the location of the point of maximum concentration. This last factor is extremely important in zoning and, in this context, should be considered along with the frequency of occurrence of different wind directions and meteorological parameters affecting atmospheric stability. Questions such as these will be considered in Phases II and III of the Argonne program subsequent to the development of the pollution dispersion model for the City of Chicago.

#### 2.4.2 Dispersion Model

In order to evaluate the proposal to extrapolate the existing stack height code represented by Figure 2.5, it is convenient to use the simple Gaussian plume model.

$$X = \frac{Q_e}{\pi \sigma_y \sigma_z U_w} \exp \left[ - \left( \frac{y^2}{2\sigma_y^2} + \frac{H^2}{2\sigma_z^2} \right) \right] \quad (2)$$

where  $y=0$  if the maximum (centerline) concentration is to be estimated.

The effective height  $H$  which requires an estimate for the plume rise  $\Delta H$  was calculated by

$$H = H_s + \Delta H \quad (3)$$

$$\Delta H = A \left[ - .029 \frac{U_s D}{U_w} + 5.35 \frac{Q_s^{1/2}}{U_w} \right] \quad (4)$$

where A is a stability coefficient from Table 2.5.

TABLE 2.5

A	Stability
2.65	unstable
1.08	neutral
.68	stable

This plume rise correlation proposed by Carson and Moses<sup>(9)</sup> is weighted heavily by data from single TVA stacks and therefore emphasizes large Q and H<sub>s</sub> values. Using the reference stack velocity (60 ft/sec) and stack temperature (500°F) specified by the DAPC, the stack diameter is represented by the function

$$D = 1.5 \times 10^{-2} Q_p^{1/2} \text{ meters} \quad (5)$$

Substitution into Equation (4) indicates that the momentum term is negligible for the parameter range of interest so that

$$\Delta H = 5.35 A Q_s^{1/2} / U_w \quad (6)$$

Following Singer and Smith<sup>(10)</sup>, several reference sets of dispersion parameters were used. These are summarized in Table 2.6.

TABLE 2.6 Dispersion Parameters after Singer and Smith<sup>(10)</sup>

CLASS <sup>+</sup>	DESCRIPTION	COEFFICIENTS <sup>++</sup>						U <sub>w</sub> <sup>+++</sup>
		a	$\sigma_y$	b	c	$\sigma_z$	d	
B1	Unstable	.36		.86	.33		.86	7
C	Neutral	.32		.78	.22		.78	10
D	Stable	.31		.71	.06		.71	6

- <sup>+</sup> Brookhaven Gustiness Classification based on an aerovane at 350 feet above ground.  
 B1. Wind direction fluctuations are from 15° to 45°  
 C. distinguished by an unbroken solid wind direction trace  
 D. wind direction trace approximates a straight line—short term fluctuations do not exceed 15°.

<sup>++</sup> Based on  $\sigma_y = ax^b$ ,  $\sigma_z = cx^d$  (7)

<sup>+++</sup> Mean wind speed at 108 meters appropriate to each stability class.

The dispersion coefficients in the form of Equation (7) are substituted into Equation (2) which can then be maximized with respect to the downwind distance  $x$ . The location and value of the maximum ground level concentration are:

$$x_p = \left\{ \frac{dH^2}{c^2(b+d)} \right\} \frac{1}{2d} \quad (8)$$

$$\chi_p = \frac{Q_e}{\pi a c U_w} \left[ \frac{c^2(b+d)}{2.72 d H^2} \right] \frac{b+d}{2d} \quad (9)$$

A computer program has been written into which one can substitute various dispersion parameters and stack height relationships to investigate these equations.

#### 2.4.3 Calculations

Using the parameters of Singer and Smith from Table 2.6 along with the present stack height code (Equation (1)) and the plume rise formula (Equation (6)), one arrives at the relationship:

$$\chi_p = \alpha_i \beta_e \quad (10)$$

where  $\beta_e$  is a constant relating plant thermal power to units of pollutant ( $Q_e = \beta_e Q_p$ ) and  $\alpha_i$  From Table 2.7 depends only upon the stability condition.

TABLE 2.7

<u>Stability Class</u>	<u><math>\alpha_i</math></u> <sup>+</sup>
B <sub>1</sub>	.012
C	.019
D	.009

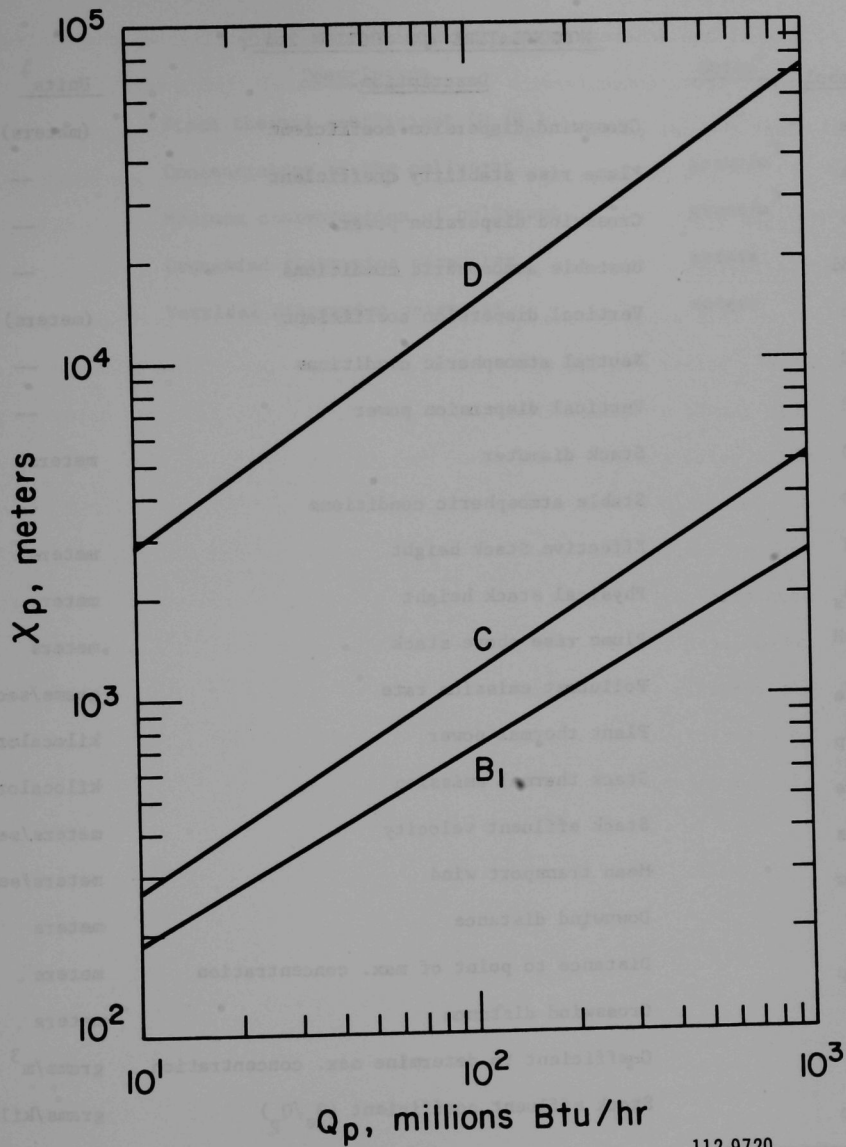
<sup>+</sup> assumed stack emits 20% of the plant thermal power, i.e.,  $\beta_s = .2$ .

Thus, if one adheres to the present stack height ordinance, the maximum ground level concentration will be approximately independent of the plant thermal power.

Plots of  $x_p$  vs.  $Q_p$  for the three stability classes are shown in Figure 2.6.

#### 2.4.4 Conclusions

This study of the Chicago stack height code, while of very limited scope, points out the consistency as well as some of the inadequacies of this rather arbitrary formulation (Equation (1)). The dispersion model while quite simple has been used by many workers to predict ground level  $SO_2$  to within a factor of 4 and often within a factor of 2. One additional sophistication which might be employed would account for the increase in mean transport wind with effective stack height. However this effect is compensated in part by the decrease in plume rise with  $U_w$ . Turner<sup>(11)</sup> in his recently published manual on dispersion modeling presents algorithms to estimate the effects of inversion layers and fumigation. These might also be incorporated in a more complete study.



112-9720

Fig. 2.6 Maximum Coordinate vs. Heat Emission

NOMENCLATURE FOR SECTION 2.4

<u>Symbol</u>	<u>Description</u>	<u>Units</u> <sup>+</sup>
a	Crosswind dispersion coefficient	(meters) <sup>-b</sup>
A	Plume rise stability coefficient	--
b	Crosswind dispersion power	--
B1	Unstable atmospheric conditions	--
c	Vertical dispersion coefficient	(meters) <sup>-d</sup>
C	Neutral atmospheric conditions	--
d	Vertical dispersion power	--
D	Stack diameter	meters
D	Stable atmospheric conditions	--
H	Effective Stack height	meters
H <sub>s</sub>	Physical stack height	meters
ΔH	Plume rise above stack	meters
Q <sub>e</sub>	Pollutant emission rate	grams/sec
Q <sub>p</sub>	Plant thermal power	kilocalories/sec
Q <sub>s</sub>	Stack thermal emission	kilocalories/sec
U <sub>s</sub>	Stack effluent velocity	meters/sec
U <sub>w</sub>	Mean transport wind	meters/sec
x	Downwind distance	meters
x <sub>p</sub>	Distance to point of max. concentration	meters
y	Crosswind distance	meters
α	Coefficient to determine max. concentration	grams/m <sup>3</sup>
β <sub>e</sub>	Stack effluent coefficient (Q <sub>e</sub> /Q <sub>p</sub> )	grams/kilocalorie

<sup>+</sup>Unless otherwise indicated.

NOMENCLATURE (contd.)

<u>Symbol</u>	<u>Description</u>	<u>Units</u> <sup>+</sup>
$\beta_s$	Stack thermal coefficient ( $Q_s/Q_p$ )	--
$x$	Concentration of the pollutant	grams/m <sup>3</sup>
$x_p$	Maximum concentration of pollutant	grams/m <sup>3</sup>
$\sigma_y$	Crosswind dispersion parameter	meters
$\sigma_z$	Vertical dispersion parameter	meters



## CHICAGO AIR POLLUTION DISPERSION MODEL

### 3.0 Meteorology

J. Carson

D. Gatz

E. Croke

### 3.0 Meteorology

The meteorological effort to date has been concentrated in four areas.

These are as follows:

1. Acquisition of the available meteorological data needed to support the diffusion studies and having them error checked and processed for inclusion in the master data file;
2. Planning a series of observational projects to provide certain meteorological and dispersion data which do not now exist, but which are needed for a full understanding of the diffusion processes over the city;
3. Development of criteria for identification of air pollution regimes and for selecting periods of similar weather conditions within a regime for statistical regression analyses; and
4. Analysis and evaluation of existing dispersion models and those currently under development.

#### 3.1 Meteorological Data

##### 3.1.1 Chicago TAM Data

A computer program to list the air quality and meteorological data at the eight TAM stations was developed and applied to 19 months of data. This program was designed to locate and identify periods of missing data. These listings were scanned for errors and corrections were made. Tapes containing data for the last five months of 1967 have been received and will be processed in a similar manner.

An examination of the data shows that large percentage changes of  $\text{SO}_2$  concentration occur within the 15-minute period between two observations at a given station, and also that the wind direction and speed data for Station 3 (GSA Building in the Loop) are unrepresentative of the area. Considerable amount of data are missing from the tape file due largely to operational problems associated with the data acquisition and recording operation.

### 3.1.2 Airport Weather Data

Magnetic tapes containing airways weather data for the three major Chicago area airports have been received from the National Weather Records Center, Asheville, North Carolina. A contract was issued to NWRC to punch the data from Meigs lakefront airport onto cards, and the data is now available at Argonne. Computer codes to convert this partly analog data into computer-acceptable form have been developed. The data from all four airport weather stations will shortly be incorporated into the master data file. Initially, the data from Midway Airport -- the only airport now in the master file -- will be used to identify weather regimes. As the program develops, it is expected that the data from the other airports, plus the Argonne observations and the wind data from the eight TAM stations, will be used in the diffusion analyses.

### 3.1.3 Upper Air Data

Magnetic tapes of the rawinsonde data from the two nearest Weather Bureau upper air stations (Peoria, Illinois and Green Bay, Wisconsin) have been received. Computer codes to plot these observations are in development. The depth of the mixing layer and the location and intensity of inversions can be inferred from these data under most but not all weather conditions.

### 3.2 Chicago Urban Meteorology Studies

To predict  $\text{SO}_2$  concentrations for Chicago, it is necessary to develop a good understanding of the phenomena which directly affect the capability of the air over the city to diffuse pollutants. It is necessary to define how this capability changes in time and space and from one meteorological "situation" to another. At this point, we can propose no more than a series of educated guesses about Chicago diffusion characteristics, since the necessary measurements have not been made. Three observational projects are being planned to eliminate or reduce this information void. The measurements required fall into two categories. The first includes direct measurements of diffusion characteristics, using a gaseous tracer. The second consists of rather fundamental meteorological measurements which will assist us to delineate and understand the important Chicago meteorological phenomena.

#### 3.2.1 Tracer Studies

Most existing computerized diffusion models are source oriented; that is, the computer solves the transport equation for each area and point source, and the pollution level at a given point is represented as the sum of the contributions from each of the individual upwind sources. An accurate forecast of  $\text{SO}_2$  concentration does not necessarily mean that the contribution from each source was correctly assessed, since a series of compensating errors may have been involved. Furthermore, unless the  $\text{SO}_2$  from a given stack is somehow tagged, there is no way to be certain that a given stack creates a certain level of pollution at various points

downwind. Legal actions to reduce pollution levels by fuel changes or mandatory reductions in the rate of release of effluents during periods of stagnation must be based on demonstrated knowledge of the behavior of the plume from that specific source.

The most direct experimental method of assessing actual diffusion conditions is to release a suitable tracer into the real atmosphere from a real stack and then measure how much the tracer is diluted when it reaches a downwind receptor. Several suitable gaseous tracers have recently been shown to be detectable at very high sensitivities<sup>(12)</sup>.

A series of tracer experiments is therefore being prepared to demonstrate the effect of one or more individual sources on the total pollution level; to check the accuracy of the plume transport calculations, and to measure the value of the dispersion coefficients under various weather conditions in the Chicago metropolitan area. It is planned to use sulfur hexafluoride ( $\text{SF}_6$ ) as the tracer gas, using the system developed and tested by the National Center for Air Pollution Control, U. S. Public Health Service, Cincinnati, Ohio<sup>(12,13)</sup>. The test procedure involves the release of the tracer gas at a rate of a few grams per second. Gas samples are collected in saran bags for subsequent analysis in a gas chromatograph. Sensitivities of one part in  $10^{11}$  are possible with this system without concentration of the sample, and one part in  $10^{14}$  with concentration. The error of measurement is of the order of 10%.

NCAPC has supplied one sample collector to initiate shakedown trials for the observational program. Argonne's Industrial Hygiene and Safety

Division will supply the gas chromatograph, modify it to accommodate  $\text{SF}_6$  analysis and perform some of the analyses. The chromatograph modification includes the construction of a new valve system and gas collector columns and the purchase of an electron capture detector. Preliminary test releases and background measurements will be made at Argonne with the help of an experienced technician from NCAPC, Cincinnati, Ohio. As part of the field trials, air samples will be collected and tested for background levels of  $\text{SF}_6$  in Chicago. Since this gas is used for spark suppression in high voltage equipment, it may prove that background levels in the city will be excessively high. In this case, two other halogenated tracer gases, bromotrifluoromethane ( $\text{CBrF}_3$ ) and octafluorocyclobutane ( $\text{C}_4\text{F}_8$ ), will be employed. These two tracer gases have been tested by NCAPC and found to be satisfactory, but they have somewhat lower sensitivities than  $\text{SF}_6$ . Since all three species are inert, nontoxic, colorless, odorless, tasteless and noncorrosive, they are virtually ideal tracer gases. Unfortunately, none of the tracer gases are removed from the atmosphere in the same manner as  $\text{SO}_2$ . For this reason, care must be exercised in interpreting the resulting data. No test runs should be made during precipitation, high humidity, or fog periods.

A preliminary plan for the conduct of these tracer studies after the shakedown tests and field trials have been completed includes:

1. Release of the tracer gas into the stack of a large plant (one of the Commonwealth Edison plants, for example) whose  $\text{SO}_2$  emission rate is known, with the  $\text{SF}_6$  receptor sited adjacent to one of the TAM  $\text{SO}_2$  detectors.

The  $\text{SF}_6/\text{SO}_2$  ratio in the stack is known, so that if  $\text{SO}_2$  and  $\text{SF}_6$  were removed from the air at approximately the same rate, the amount of  $\text{SF}_6$  at the receptor point would be a measure of the  $\text{SO}_2$  from that individual source. Such experiments should be conducted under low humidity conditions so that the removal of  $\text{SO}_2$  is at a minimum.

The observed  $\text{SO}_2$  levels from an individual source would then be compared to that predicted from the transport equations used in the diffusion model, and the correct dispersion coefficients would be estimated. An extensive series of such measurements should yield considerably more accurate estimates of these parameters than are now available. A variation of this experiment would involve simultaneous release of two or three different tracer gases from separate major sources. Thus, the diffusion rate from several sources could be measured in a single experiment.

2. The tracer gas could be placed in a large pollution source outside of the city which is not included in the hourly emission inventory, such as the Romeoville Commonwealth Edison plant. The amount of tracer gas detected would then indicate the amount of  $\text{SO}_2$  from that major background source which actually arrives at the edge of the city.

3. The tracer gas could be used to estimate more accurately the probable pollution distribution patterns produced by a new factory or other major source before a construction permit is granted. The tracer gas would be released in a manner similar to that for the proposed industrial stack and the downwind concentrations of  $\text{SF}_6$  could be measured.

4. Most diffusion studies to date have been in rural areas. Little is known about the difference between diffusion rates over cities (with

their greater surface roughness, local heat sources, multiple small pollution sources, etc.) and rural areas. If sufficient manpower were available, an extensive series of measurements could be made in several "typical" sectors of Chicago, such as areas of single family dwellings, extensive areas of six flat apartments, areas containing multiple high rise apartments, the Chicago Loop, park green belts, etc. The tracer gas could be injected into a local stack and a series of samples could be placed from one to four kilometers downwind on a line orthogonal to the prevailing wind direction. The observed crosswind pollution profiles would yield data on the diffusion coefficients.

5. Much of the short term variability of  $\text{SO}_2$  at each TAM station may be due to small, intermittent sources located relatively near the receptor. If this is the case, attempting to predict  $\text{SO}_2$  concentrations using data from relatively few large sources may not be a valid procedure. Small amounts of  $\text{SF}_6$  could be released from these low level, suspected sources and measured at the receptor site to determine their effect on the local levels of  $\text{SO}_2$  concentration reported by the TAM station.

### 3.2.2 Stability Measurements

Concurrently with direct diffusion measurements by means of tracer techniques we will attempt to assess by other means, the diffusion characteristics of several different meteorological situations common to Chicago. This effort will consist in measuring the three-dimensional temperature structure of the atmosphere over the city, and hence its stability.

The diffusive capability of the urban atmosphere varies greatly with time and location. In all cases, however, that capability is determined to

a great extent by the vertical stability of the atmosphere, which is determined, in turn, by the vertical temperature distribution. Two concepts are involved: the first is the intensity of mixing; the second is the depth through which mixing occurs. Both may be specified from the vertical temperature distribution. At present, very little is known about the ability of the air over Chicago to mix and diffuse pollutants, because no measurements of the temperature variation with height are available. Daily vertical temperature measurements are made in nearby rural locations but these measurements cannot be directly applied to the city because city and rural surfaces possess different thermal properties. Therefore, it is necessary to measure the vertical temperature distribution in the lowest few thousand feet over the city -- within the zone of influence of the local urban "heat island." To understand the temporal and spatial variations of the temperature profile, it is necessary to make measurements at many different times throughout the year and at various locations throughout the city.

Vertical temperature measurements will be made in two ways:

1. by means of an instrumented helicopter
2. by means of sensors mounted atop several, centrally located, tall buildings of different heights.

In addition, an existing array of nine hygrothermographs sited on a NE-SW line parallel to the Stevenson Expressway provides continuously recorded temperature and moisture data between the lakefront and the Argonne meteorological station.

### Helicopter Sounding Program

The City of Chicago Department of Air Pollution Control (DAPC) has purchased an airborne instrument package designed to measure  $\text{SO}_2$  concentration, air temperature, dewpoint temperature and pressure altitude from an aircraft or helicopter. The DAPC has made arrangements for a City Fire Department helicopter to fly this equipment.

The objectives of the helicopter sounding program are: (1) to evaluate atmospheric and diffusion conditions (such as the horizontal and temporal variations of the urban lapse rate; the height, base, and thickness of inversions, the depth and extent of penetration of lake breeze circulation and the altitudes of maximum  $\text{SO}_2$  concentration, etc.) for a number of "typical" weather situations, (2) to relate the observed upper air conditions to the standard Weather Bureau surface and rawinsonde observations, and to enable prediction of dispersion parameters from standard weather bureau data.

Argonne's role in this program is to design the flight program and to analyze the resultant data inventory. Experience with similar programs in Cincinnati<sup>(14)</sup> and New York City<sup>(15)</sup> will aid in the development of the flight program. The helicopter will normally fly in a saw-tooth pattern, rising from nearly ground level through the transport and mixing zone to an altitude of about 2000 to 3000 feet and then descend while moving horizontally along the intended route. An automobile mounted sensor, traveling along the same route and in radio contact with the helicopter, will probably be required in order to provide information regarding the temperature profile at ground level.

Four flight patterns have been proposed for the initial stages of the program:

1. During a period when steady winds from the WNW, W or SW are expected for 12 to 18 hours, the helicopter will traverse a series of vertical profiles along the direction of the wind from a point over the lake to the rural and suburban areas west of the city. The flight route could be along an expressway, with surface observations obtained from the automobile traveling below the helicopter.

Flights should begin as early in the morning as is possible, and continue through the day into the night. This series of flights would indicate how the nocturnal rural inversion is altered as the air moves over the city (heat island effect); how the depth of the mixing layer varies with altitude and time at a given location and how the nocturnal regime is established. It would also identify layers of high  $\text{SO}_2$  concentration. In some cases, it may prove to be possible to follow the smoke plume from a single large source and compare its motion and dispersion with that calculated by the theoretical model.

2. During a period in spring or summer when an east wind is expected to persist for 6 to 12 hours, the helicopter and automobile will be used in a pattern similar to that described above. These flights would show the rate at which this clean, cold, stable air entering Chicago during this season is heated from below, and how dispersion characteristics vary with distance inland. These data should be of considerable interest to mesometeorologists studying the dynamics of this thermal circulation.

3. During periods of low windspeed and high pollution buildup, numerous verticle profiles will be obtained at many locations over the city.

These will include rural areas, the Argonne site (to compare helicopter lapse rates with Argonne meteorological tower observations) and over Lake Michigan. Almost nothing is known about dispersion conditions over the city under these conditions; thus information which indicates how lapse rates vary with time and space, how the lapse rate is affected by the heat island effect, the structure, height, thickness, and intensity of inversion layers, and the locations of stratified layers of high and low  $\text{SO}_2$  concentrations, etc., will be of considerable value.

4. During a period when a true lake breeze is expected, observations will be made before, during and after the lake breeze. These flights must go high enough to penetrate the upper boundary of the lake air in order to determine the vertical extent and circulation of the system. A series of vertical ascents and descents will be made along a path at right angles to the lake shore in order to measure the rate of modification of the cold air as it moves across the warm city and the rate at which  $\text{SO}_2$  is added to the clean air. The  $\text{SO}_2$  buildup in the zone of convergence along the lake breeze "front" is also of interest. At present, almost no information is available regarding the details of actual flow during a lake breeze situation.

This series of four flight programs represents the current level of planning for the sounding program; experience plus the availability of funds and manpower for the flights and for data reduction will determine the total program. It is hoped that meteorologists interested in meso-circulations such as those described above will be able to use these data in their studies and will propose schemes for making future flights more productive.

### Instrumentation of Tall Buildings

The helicopter is an ideal sensor platform for obtaining data over large areas rapidly and at moderate cost. Unfortunately, it does not permit continuous observations to be made.

Discussions have been held with the architects of the John Hancock Building which is now under construction in the central Chicago business district. Arrangements have been made to place one aspirated temperature sensor on each of the two T.V. towers atop the building. These sensors will be about 1200 feet above ground level -- 100 feet above the building itself. Another sensor will be located about 150 feet above ground level on the nearby Chicago Water Tower. The City Department of Air Pollution Control will shortly begin discussions with the operators of one or two intermediate sized buildings in the same area to obtain sites for additional sensors, so that temperature profiles from street level to 1200 feet can be measured on a continuous real-time basis. It is recognized that exact temperature profiles cannot be measured in such a manner, due to such factors as heat from buildings, obstructions to wind flow and the fact that the sensors are not placed vertically, but for the purpose of conducting diffusion analyses, information on the lapse rate class (inversion, isothermal, near neutral or unstable) is the type of data that is actually needed.

The accuracy of building sensor data can be tested by having the helicopter fly at the altitude of the sensor but away from the heat of buildings. If these building-mounted sensors prove useful, a break-through in

city pollution meteorological observations will have been achieved. Similar observations could be made in other cities at a minimum cost.

In summary, the diffusion characteristics of some common Chicago meteorological phenomena are poorly understood. We plan to measure diffusion conditions directly, using  $\text{SF}_6$  gaseous tracer for a number of source-receptor-meteorological condition combinations. Not all combinations can be tested, however; to complement these tests and fill gaps in our knowledge of Chicago's diffusion meteorology, we will measure the vertical temperature structure using instruments mounted on tall buildings and on a helicopter. From these measurements we hope to evaluate diffusion conditions with sufficient skill to implement accurate predictions of Chicago  $\text{SO}_2$  concentrations under most prevalent meteorological conditions.

It should be noted that the realization of directly useful results from the field measurements is many months away, and will not be available until after the preliminary diffusion model has been developed and is in the testing stage. Priority of effort must be given to developing the best possible diffusion model within the constraints imposed by the available data inventory,

### 3.3 Weather Classification

The general formulation of our statistical diffusion model is based on the development of a set of regression equations to predict  $\text{SO}_2$  concentrations for each TAM receptor site. Each set of equations will eventually cover all, or nearly all, meteorological conditions which might occur at the receptor. Thus, whatever the weather condition, an appropriate

empirical equation to predict  $\text{SO}_2$  at the receptor will be available. This concept requires that weather classifications be so developed that diffusion conditions are essentially constant during all occurrences in a given class. It is important that the classifications be based on predictable parameters, because the model will ultimately be used for operational purposes.

This approach requires an effective and practical classification of weather occurrences. The preliminary classification scheme is a dual one, composed of a general class -- the "regime" -- and a more quantitative set of meteorological parameters -- the "met. set".

A meteorological regime, as the term is used here, is the general synoptic framework in which a local weather pattern occurs. Thus, we may eventually specify regimes in terms of surface and 500 mb analyses. As a first trial, however, we plan to use a limited list of general weather conditions, formulated on the basis of local experience and a recent air pollution climatology study<sup>(16)</sup>. This list includes such conditions as anticyclonic stagnations, lake inversions, nocturnal inversions, and steady wind conditions.

The met. set is an aggregate of surface meteorological parameters, plus season and time of day, which, together with the regime, classification, specifies diffusion conditions. The parameters to be included in the initial trials are:

Wind speed: Three speed ranges.

Wind direction: 0 to 360 degrees, in increments of  $20^\circ \pm 20^\circ$ . Thus each class includes a  $49^\circ$  arc when rounding-off practices are considered. For example, the  $20^\circ$

direction class includes actual winds between 355° and 44°.

Cloudiness: In two classes; the dividing line between cloudiness classes may differ for night and day conditions. For example, the nocturnal cloud cover may be partitioned at 0.5 while the diurnal may be partitioned at 0.8.

Measurable precipitation: Two classes -- the presence or absence during a given hour or the hour preceding of precipitation in greater than trace amounts.

The daily and seasonal parameters chosen for first trials are:

Season: Winter (December, January, February)  
 Spring (March, April, May)  
 Summer (June, July, August)  
 Fall (September, October, November)

Time of day: Night: 2 hours after sunset to 2 hours before sunrise  
 Day: 2 hours after sunrise to 2 hours before sunset  
 (Transitional hours -- 2 hours before and after sunrise and sunset -- will be excluded from the first trials).

### 3.3.1 Illustrative Example

One particular combination of regime and met. set for which a particular regression equation for  $\text{SO}_2$  prediction will be written, might be:

Regime:            stagnating anticyclone

Met. set:

Season: summer

Day/Night: Night

Cloudiness: 5/10

Wind speed: 4 m/sec but not calm

Wind direction:  $180^\circ \pm 20^\circ$

Precip/no precip: no precipitation

To form the regression equation for this combination of regime and met. set, we will use those hours of source inventory data for all significant upwind sources and those hours of meteorological observations from Midway Airport in 1966 and 1967 which qualify for the met. set. Initially, we will reject lake breeze situations. These we will identify on the basis of wind speed and direction disparities between two TAM stations near the lake and Midway Airport. This scheme will identify about half of the lake breeze situations -- the other half will pass Midway and give rather uniform conditions at all three stations. When Argonne wind data are added to the master data file, we will compare Argonne winds to lakefront winds to identify lake breezes. The hygrothermograph data, when added, will also help in lake breeze identification.

3.4 Spring Emission Control Test Series

The spring 1968 emission control tests to be conducted by Argonne and the City of Chicago are designed with two distinct objectives:

1) The Chicago DAPC wishes to conduct preliminary field trials of the procedures necessary to implement a realistic and effective  $\text{SO}_2$  abatement strategy. This implies the establishment of a methodology for converting major, dual fuel coal and oil burning sources to natural gas; shifting power loads of major generating stations to upwind or extra-urban plants and maintaining a real-time surveillance of the operating status of other high sulfur fuel users. (More sophisticated and economically disruptive control measures such as the delay or curtailment of certain industrial processes are not yet feasible). The abatement strategy required for this level of pollution control involves the ability to implement a fuel use control plan on relatively short (24-48 hours) notice, and to maintain this control for the duration of a major pollution incident (6-72 hours).

2) The Argonne  $\text{SO}_2$  dispersion studies require that emission control tests be conducted in such a way that the pollution dispersion characteristics of a well-defined meteorological regime be experimentally established in terms of the transport of  $\text{SO}_2$  from known sources to the TAM receptors. This implies that the emission control tests must take place during an appropriate meteorological regime (stagnating anticyclone, lake breeze, nocturnal inversion, etc.) and must be long enough in duration (2-72 hours) to allow the air quality measured at a given TAM receptor to achieve a quasi-steady-state value which is characteristic of the city-wide  $\text{SO}_2$  emission pattern and the prevailing meteorological

situation. Further, if possible, the emission control program should be such that the SO<sub>2</sub> sources can be "pulsed" during the course of a single meteorological regime so that it will not be necessary to factor out differences between two similar but not identical situations in evaluating the effects of source control on air quality.

The two objectives described above are by no means incompatible, but in order to satisfy both, it is necessary to establish certain ground rules for the emission test series. These must not only correspond to the requirements of the DAPC and Argonne, but must be compatible with the degree of control that the DAPC is capable of imposing on the city's coal and oil users and with the realities of meteorological forecasting. These ground rules are as follows:

- 1) The emission control plan must be based on the ability to provide a maximum advance notice of 24 hours to the coal and oil users. Since it is essential that the tests take place during an appropriate meteorological regime, the date and time for the initiation of the tests must be based on a meteorological forecast. It is neither feasible nor practical to rely upon detailed meteorological forecasts beyond a 24 hour interval; hence this constraint is necessary and is, in any case, compatible with the kind of control operation that the DAPC will have to mount if pollution abatement planning is to become a practical reality. The 24 hour advance notice can be coupled with a 48 hour alert period if a fuel user expresses the need for additional warning of an impending test.

- 2) The control plan must be predicated on a minimum control interval of eight hours. This requirement is dictated by the assumption that practical emission control will have to be based on the unit of time

that is "natural" to an industrial plant - the working shift. The disruption of normal operations that is attendant on a fuel switch at the time of a shift change is minimal and therefore most acceptable to the plant operators with whom the DAPC must deal.

3) The meteorological regimes selected for the tests must be those that are likely to prevail for a minimum of 12 hours. This requirement is directly related to the eight hour pulse duration discussed above; to the necessity of assessing the effects of an on-off pulse within the lifetime of a single meteorological regime and to the desirability of evaluating diurnal effects.

4) Several alternative meteorological regimes must be preselected as suitable for the spring tests. These should be of a kind which are likely to yield relatively high SO<sub>2</sub> concentrations at key TAM stations such as Hyde Park, and for which there is a relatively high probability of occurrence. This policy will maximize the likelihood of encountering appropriate test conditions.

5) The test series must be so devised that the effects of controls imposed on Commonwealth Edison plants can be separated from the effects of control of industrial emissions, but the capacity for total emission control must also be assessed. This implies a minimum of three eight hour pulse tests:

- a) Edison on coal with industry on gas
- b) Edison on gas with industry on coal
- c) Edison and industry on gas.

Ideally, these three kinds of tests would be conducted within the

lifespan of a single pollution regime which would have a minimum duration of three days. The probability of achieving such test conditions is not particularly high, and it would not be appropriate to implement three eight hour pulses in a single 24 hour period because of the complications introduced by diurnal effects on atmospheric stability. In consequence, a contingency plan for a three day test will be developed, but one and two day contingency plans will also be prepared.

Three one-pulse-per-day tests conducted during similar meteorological regimes which may be separated by an interval of several days or weeks constitute an acceptable test series, but the results are likely to be more difficult to interpret because of the inevitable dissimilarities between "similar" regimes.

A regime which persists for two consecutive days offers the opportunity to conduct two of the three types of tests under appropriate test conditions. The probability of persistence of a two day regime is, of course, higher than for a three day situation, hence a contingency plan will be prepared for this possibility. It is likely that such a plan will consist of no more than a truncated version of a three day test series. In any case, it is necessary to provide for continual updating of the meteorology forecast during the course of a test in order to make decisions on whether to continue testing or terminate the series.

In view of these ground rules, the DAPC, as the agency which will administer the emission control tests, must arrange for the participating dual fuel users to anticipate from one to three fuel switching operations within three consecutive days. That is, an operating sequence of the kind

tabulated below is required:

<u>Time</u>	<u>Day</u>	<u>Industrial</u>	<u>Utility</u>
0800 DST	1	On Gas	On Gas
0800 DST	2	On Gas	On Coal
0800 DST	3	On Coal	On Gas
Number of Switches		2	3

The participating fuel users must be advised of the duration of the period during which tests may be implemented, but for practical purposes, need not be aware of all possible contingency plans so long as they are prepared to cope with a test which may be as much as three days in length and which may involve up to three fuel switches.

The DAPC will prepare fuel use forms which will be distributed to all participants, whether or not they possess dual fuel switching capability. These forms will be used to record hourly fuel consumption, fuel switching times, fuel type and sulfur content. Because of the relatively short notice which can be given for the initiation of a test, the DAPC will arrange for telephone notification of key personnel at the participating plants.

It is also necessary to arrange for monitoring of natural gas use rates during the course of a given test. In view of the excellent recording procedures employed by the local gas supplier, this should be relatively easy to accomplish. The monitoring effort will provide a partial check on the degree of compliance of participating dual fuel users with the proposed test plan, and will enable a practical assessment of the impact of pollution abatement planning on the availability of natural gas - a commodity which, in the near future at least, appears

to be the key element in rendering  $\text{SO}_2$  emission control a feasible undertaking.

It is expected that approximately 50 major high sulfur fuel users will participate in the projected tests. These account, in the aggregate, for about 80% of the total, annual  $\text{SO}_2$  emissions within the city limits. It is obviously rather significant that the Chicago DAPC is in a position to impose  $\text{SO}_2$  emission controls on such a large segment of the city's fuel users, but it is necessary to note the existence of several significant omissions in this or any similar emission control effort.

1) A number of major high sulfur fuel users are outside the city limits. These are not subject to control, nor are the magnitude and effect of their  $\text{SO}_2$  emissions on air quality within the city known at present. These extrarurban sources include large plants in the Cicero, Illinois industrial complex, the Gary-Hammond industrial concentration and certain very large power stations such as the Romeoville, Illinois Edison plant. These undoubtedly contribute significantly to the  $\text{SO}_2$  background in Chicago, given appropriate meteorological situations, but they have not as yet been subjected to appropriate study. It is unlikely that any realistic assessment of the effects of such sources can be made until the  $\text{SF}_6$  tracer test series (see section 3.2) has been expanded to include such major, extrarurban fuel users. The accelerating Cook County air pollution control effort may, in due course, render practical an emission control test series which includes many of these sources.



## CHICAGO AIR POLLUTION DISPERSION MODEL

### 4.0 Emission Inventory

E. Croke

J. Roberts

#### 4.0 Emission Inventory

##### 4.1 General Discussion

The methodologies to be employed in the development of an hourly  $\text{SO}_2$  emission inventory for Chicago covering the period January 1966 through December 1967 were described in some detail in the first quarterly progress report (ANL/ECC-001); hence the present discussion will be confined largely to a summary of the current status of the effort.

The objectives of the emission inventory phase of the program are to develop hourly  $\text{SO}_2$  emission data for the six major, coal-burning Commonwealth Edison power plants within the city limits; for the 100 largest industrial, coal and fuel oil users and for all commercial and residential, space-heating  $\text{SO}_2$  sources. This body of data, stored in the master computer data file, will be merged with meteorological and air quality data in a multiple linear regression analysis computer code to statistically develop source-receptor coupling coefficients for the eight TAM stations of the Chicago air quality monitoring network.

As described in the first quarterly report, the methodologies employed to generate inventory data for the four different types of  $\text{SO}_2$  producers vary considerably, and, to a certain extent, reflect the relative magnitudes of the respective sources involved. Since the six Edison plants account for about 65% of the coal consumed annually in Chicago, it was deemed appropriate to seek the most detailed possible fuel use data for these installations -- a lengthy and time consuming process in both the data acquisition and processing phases. Actual hourly data was available and was acquired for these large plants.

The 100 largest industrial sources accounted for 85% of the total industrial  $\text{SO}_2$  released in the city, but none of these were comparable in magnitude to any one of the Edison plants; hence the emission inventory for such plants aimed at the acquisition or development of what was basically shift or daily fuel use data which could be reduced to approximate hourly data by appropriate analysis of the operating cycle of a given plant.

Commercial and residential space heating  $\text{SO}_2$  sources were found to be significant in their aggregate, since they account for 8.3% and 14.5%, respectively, of the city's annual  $\text{SO}_2$  production. These sources were so numerous and widespread that it was clearly impractical to acquire and process fuel use data for more than a few of the largest. Rather, enough data was accumulated to mount a statistical study of space heating fuel use patterns for large and small commercial and residential structures. A small experimental fuel use study was also initiated in support of this effort.

The correlations developed during these statistical and experimental studies will constitute the commercial and residential subsets of the computerized emission inventory data file.

#### 4.2 Power Generating Stations

With the full cooperation of the Commonwealth Edison Company, an effort was mounted to develop hourly fuel use data for each of the six major power plants within the city limits. In the order of their significance as  $\text{SO}_2$  sources, these plants may be listed as follows:

<u>Plant Designation</u>	<u>SO<sub>2</sub></u>	<u>SO<sub>2</sub></u>
	<u>tons per year</u>	<u>percent of city total</u>
Crawford	107,954	18.97
Ridgeland	100,540	17.67
Fisk	73.438	12.90
Stateline	70,606	12.42
Northwest	10,566	1.86
Calumet	<u>10,016</u>	<u>1.76</u>
	373,120 tons	65.58%

For each generator of each plant, it is necessary to obtain monthly coal consumption and coal sulfur content data, hourly power production and natural gas consumption data and a set of system efficiency curves which reflect the variation of boiler and turbine efficiency with power level. This information is extracted from Edison tabular records and gas charts and is recorded in a form suitable for computer data input. The data is then punched onto computer cards and is processed on the Argonne CDC 3600 computer. The differences in plant structure, data recording procedures, equipment, etc. among the six Edison installations are sufficiently great that it proved to be most efficient to develop a separate processing code for each plant rather than to expend the time necessary to achieve complete generality in a single computer program.

At present, data for the Fisk, Crawford, Ridgeland and Northwest plants has been received at Argonne. Processing is essentially complete for the first three of these plants and is currently in progress for the

fourth. It was originally expected that processing of the entire group of six plants would be completed by the end of the present quarter, but this schedule was not realized for two reasons:

1) The acquisition of raw data for each plant proved to be a considerably more time consuming process than was indicated by the effort initially expended at the Fisk plant in January 1968. This is largely due to the complications introduced by the fact that the Crawford and Ridgeland installations use very large amounts of natural gas in a multiplicity of boiler - generator combinations. The process of extracting gas use information from circular chart records is a lengthy and tedious one; thus, despite the fact that a DAPC engineer and an Argonne technical specialist were available to mount a fairly intensive data reduction effort during February and March, the information required was slow in coming.

2) The development of data processing codes to generate hourly SO<sub>2</sub> emission data was paced by the rate of data acquisition. Moreover, what should have been a fairly straightforward data processing effort was complicated, to some extent, by the necessity of coping with periods when certain of the generator units operated with a combination of coal and gas burned simultaneously in the same boiler.

As a result of these perturbations of the original schedule, it is now expected that the power plant emission inventory will be completed by July 1, 1968. It should be noted, however, that for the purpose of initiating the shakedown tests of the statistical procedure and for the completion of the Hyde Park TAM station pilot study, the Fisk, Crawford and Ridgeland data is of primary importance. The Northwest, Calumet and

Stateline data is essential for the analysis of other TAM stations local to these plants, but this information is largely peripheral insofar as the initial statistical diffusion studies are concerned.

#### 4.3 Industrial SO<sub>2</sub> Sources

The effort to develop shift-oriented hourly emission data for the 100 major industrial SO<sub>2</sub> sources in Chicago consists of two basic elements: data acquisition, and recording; and data analysis and processing.

##### 4.3.1 Data Acquisition and Recording

The quality and type of fuel use data retained by the members of Chicago's industrial community varies significantly from one plant to another. Some firms retain detailed and accurate hourly or shift-oriented boiler room logs which require only a minimal effort to acquire and analyze. Others can supply nothing more than rather sketchy monthly, quarterly or annual records of fuel consumption. The situation is further complicated by the fact that many of the major industrial plants possess dual fuel capability. That is, they are "interruptable" or "dump rate" customers of the local natural gas supplier and are able at frequent and unpredictable intervals to switch their heating or processing furnaces from high-sulfur fuels to gas.

Four kinds of information are required for the development of the hourly industrial emission inventory.

- 1) Fuel use data must be obtained for each plant included in the inventory.
- 2) The hourly, weekly and holiday operating cycles that are characteristic of the plant must be determined in order to

resolve the shift, daily, weekly, monthly, etc. fuel use data for a given plant into an hourly emission pattern.

- 3) The natural gas use record of each plant which possesses dual fuel capability must be acquired in order to identify the hours during which the plant operated without burning high-sulfur fuel.
- 4) The physical characteristics of the plant, i.e., its stack geometry, stack operating temperatures, etc. must be acquired in order to permit estimates of smoke plume rise to be computed.

#### Hyde Park Pilot Study

As described in the first quarterly report, a pilot study of twelve industrial plants located in the vicinity of the Hyde Park TAM station was initiated. One of the primary purposes of this study was to develop and evaluate data acquisition and processing techniques for this portion of the emission inventory effort. In particular, the pilot study was intended to serve as a test of a questionnaire designed to yield the necessary plant fuel use data. If the questionnaire technique proved successful, then the remainder of the industrial survey could be conducted by mail.

A field representative of the DAPC visited each of the plants selected for the pilot study and undertook, through the medium of the questionnaire, to obtain the required information. It became evident, even during the early stages of this effort, that the questionnaire approach was, of itself, quite inadequate for the purpose. The failure of the method was attributable to several factors:

- 1) It was not possible to insure that the questionnaire would reach the individual in each plant who was most likely to possess the required information.
- 2) Plant operators, while generally willing to cooperate with the effort, were either not prepared to volunteer information at the level of detail required or were not prepared to expend the time and effort necessary to accumulate and record this information on the questionnaire.
- 3) Where plant operators were prepared to cooperate to the fullest extent in supplying the required information, they were often unable to react rapidly enough to satisfy the schedule established for the pilot study.
- 4) It proved difficult to convey a sufficient understanding of the requirements for plant operating cycle data to insure that the questionnaire would be properly filled out.

In view of the fact that the effectiveness of a questionnaire technique tends to be inversely related to the length and complexity of the questionnaire, the limited success of the questionnaire scheme employed for the Hyde Park pilot study is readily explained. In recognition of this principle, the DAPC has developed an extremely simple punch card questionnaire scheme in order to implement its annual emission inventory program. This method, which is quite adequate for its purpose, was described in the first quarterly progress report<sup>(1)</sup>. Unfortunately, the method does not lend itself to the acquisition of the much more detailed information required to construct an hourly industrial emission inventory.

Although the questionnaire data acquisition scheme was generally inadequate, the Hyde Park pilot survey was quite successful in acquiring the necessary plant operating data and in developing a methodology for the continuation of the industrial inventory. As a result of this pilot survey, a personal interview procedure was devised, which has proven to be quite effective in the development of plant operating cycle information and the acquisition of fuel consumption records. At the time that this report was prepared, data for thirty of the city's major industrial plants had been received at Argonne.

As data for each industrial plant included in the survey is received, the fuel consumption records are reviewed for inconsistencies, omissions or other anomalies. They are then stored, according to a standard format, on computer cards. Approximately one man-day of effort is required to produce a computer card record of daily fuel use data from a given plant for January 1966 through December 1967.

Appendix I of this report includes a tabulation of stack geometry and temperature data for 28 of the 30 plants thus far surveyed. At the current rate of data acquisition and analysis, it is expected that the survey of all 100 plants will be completed by the end of August 1968. This estimate could be compromised by the fact that the smaller plants which will be surveyed during the latter part of the effort are less likely to retain detailed fuel consumption records than are large firms--hence the data analysis procedure may be more difficult and prolonged. If this should prove to be the case, the diffusion analysis effort will

not be seriously compromised, since the fifty largest industrial plants in Chicago account for over 77% of the total annual industrial  $\text{SO}_2$  production. Thus, when the 100 plant survey is only half completed, the greater part of Chicago's industrial high-sulfur fuel consumption will be incorporated in the Argonne emission data file.

#### Gas Consumption Data

The acquisition of natural gas consumption data for "interruptable" and "dump rate" gas users proved to be neither feasible nor in many cases possible through the interview technique employed at each plant. Fortunately, this type of data was available from the records of the People's Gas, Light and Coke Company (PGLC) in a far more accessible and tractable form than that which could be supplied by any individual PGLC customer.

For the purposes of this study, the amount of gas used by any "interruptable" gas user is of no particular interest. It is most important, however, to determine those time periods when a given plant was using gas instead of high-sulfur fuel, since its  $\text{SO}_2$  production during these periods is effectively zero.

PGLC divides its list of interruptable customers into six blocks, according to the price that the customer is willing to pay for interruptable gas during the heating season. The availability of gas is more or less proportional to the price paid by the customer. PGLC records indicate the date and time that interruptable gas was made available and curtailed for each customer.

A certain unpredictable lag is encountered between the time that a customer is advised that gas is available and the time that a fuel switch is effected. Moreover, a customer need not accept an offer of gas, thus a record of gas availability is not necessarily a record of gas use. It is nevertheless true that a gas offer is normally accepted, and that a time lag on the order of one hour usually accompanies a fuel switch operation -- thus the records supplied by PGLC are a generally reliable indicator of the gas use pattern of a given industrial plant. Fortunately these records are quite amenable to computer storage. They have been incorporated into the emission data file and are now in active use as a part of the industrial plant data processing effort.

#### 4.3.2 Data Analysis and Processing

In order to reduce the fuel consumption records of a given plant to meaningful hourly  $\text{SO}_2$  emission data, it is necessary to obtain information concerning the operating cycle of the plant. This includes:

- 1) Estimates of the hourly distribution of shift or daily fuel consumption in terms of the working shift pattern or production schedule of the plant.
- 2) Estimates of the daily breakdown of weekly fuel consumption in terms of the weekday vs. weekend operating pattern and policies of the given plant.
- 3) Statements of the holiday, vacation and shutdown periods and policies of the plant.
- 4) Estimates of the process vs. space heating fuel use patterns of the plant.

The amount of information required naturally varies from plant to plant and is strongly dependent on the detail with which fuel use records are maintained. A plant which retains monthly fuel use records and has dual fuel capability will require more analysis than one which maintains daily records and can burn only a single fuel.

On the basis of the plant cycle information provided through the interview survey technique, up to three sets of dimensionless operating patterns are developed for a given plant -- depending on the type of fuel use data that it can provide. These are:

1) Daily Pattern Sets

These divide a plant day into 24 one-hour periods and assign a fraction of the daily fuel use to each hour. As many as three patterns may be required to characterize a normal work week -- one for weekdays, one for Saturdays and one for Sundays and holidays, etc.

2) Weekly Pattern Sets

These are developed to identify which daily pattern set should be applied on a given day. Some plants, such as bakeries, tend to work a normal production schedule on Sundays and holidays and adopt a shutdown schedule on one or more weekdays and days before holidays. The weekly pattern set assigns the proper daily pattern to each day of the week.

3) Monthly Pattern Sets

In the event that a plant experiences a monthly production cycle, this pattern set establishes the distribution of fuel use on a weekly basis throughout the month.

One or more of these pattern sets are established for each plant and, in combination with the natural gas availability data, are employed in a computer processing operation to develop hourly fuel consumption and  $\text{SO}_2$  emission data for each plant. The fuel used by a given plant is automatically distributed over those hours when the plant was not burning natural gas, according to daily and weekly patterns which are characteristic of the plant.

The development of computer data processing techniques for use with the data inventory and pattern sets was one of the major efforts undertaken during the past quarter. In the initial stages, this effort has proceeded rather slowly because of the necessity of constructing basic subroutines which can be used repeatedly with different plants. These subroutines include a computerized calendar for 1966-67, a natural gas availability and distribution algorithm, a missing and spurious data identifier, an operating pattern storage and selection algorithm and various input-output routines to accommodate the several formats associated with different types of plant data. The output of a given processing operation is a deck of punch cards containing hourly  $\text{SO}_2$  emission data for the two year period under study.

During the course of development of the subroutines and algorithms required for the industrial plant data processing effort, five plants in the Hyde Park "sphere" were completely processed and data was supplied for use in the master emission file. The processing effort should accelerate rapidly as these standard subroutines are applied to data for other plants.

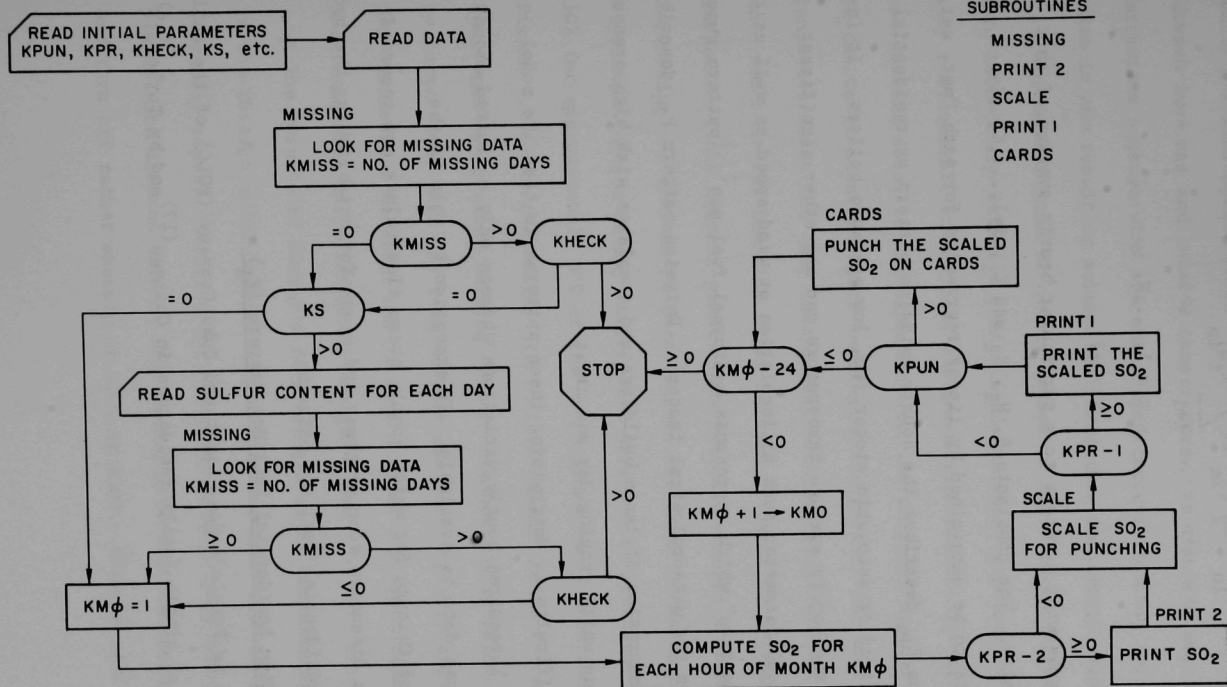
It is intended that the aggregate of subroutines, algorithms, input-output routines and data filtering routines that have been developed for the industrial data processing effort will, in due course, be combined into a general, industrial plant simulation code. This code, dubbed PLANTSIM, will have an input scheme which is sufficiently general that shift, daily, weekly or monthly plant data and pattern sets can be routinely read in and hourly fuel use data generated by activating whatever processing options are appropriate to the type of data to be processed. Figure 4.1 shows the computer flow chart for the existing, preliminary version of PLANTSIM.

PLANTSIM will not only be of use in the present Argonne hourly emission inventory effort, but may also be an integral part of the DAPC air pollution control and abatement program, since that organization will eventually have to be in a position to assess the probable hourly emission patterns for the city as a part of any effective emission control operation. In this context, a version of PLANTSIM could be used to simulate the industrial emission pattern for the entire city at any given hour of the day.

In anticipation of this possibility, the DAPC has undertaken to introduce the acquisition of plant operating cycle data into its routine field inspection procedures. This will serve to maintain and update the currency of the data accumulated for processing in PLANTSIM.

#### 4.4 Commercial and Residential Heating Studies

The statistical approach to the construction of a dispersion model is based on the linear superposition of sources in the form<sup>(1)</sup>:



# SUBROUTINES

MISSING  
PRINT 2  
SCALE  
PRINT 1  
CARDS

112-9721

Fig. 4.1 PLANTSIM Flow Diagram

$$\chi_n = B + H_1 P_{1n} + H_2 P_{2n} + \sum_{i=1}^I K_i Q_{in} \quad (1)$$

$$n = 1, \dots, N$$

$$N > I+3$$

where the subscript  $n$  refers to a particular hourly average of that known quantity. The constants  $B$ ,  $H_1$ ,  $H_2$  and  $K_i$ ,  $i=1, \dots, I$ , are coefficients to be determined by linear regression for each "met. set." The function  $P_{1n}$  describes the hourly emission pattern or residential with hand-fired or automatic stoker fed, low pressure boilers. It incorporates the hourly average temperature and any other significant meteorological parameter such as insolation or wind speed as well as the "janitor function" which represents a diurnal fuel use<sup>(1)</sup> pattern superimposed upon the meteorological factors. Emission pattern  $P_{2n}$  describes the fuel consumption of large buildings and complexes with high pressure steam heating units running day and night.

The difficulty in determining these patterns is that the model (Equation 1) requires hourly variations whereas only a limited amount of daily fuel use data is available. An exception to this is the University of Chicago for which hourly steam flow values are recorded. This section discusses some progress and plans for establishing the two commercial-residential fuel use patterns.

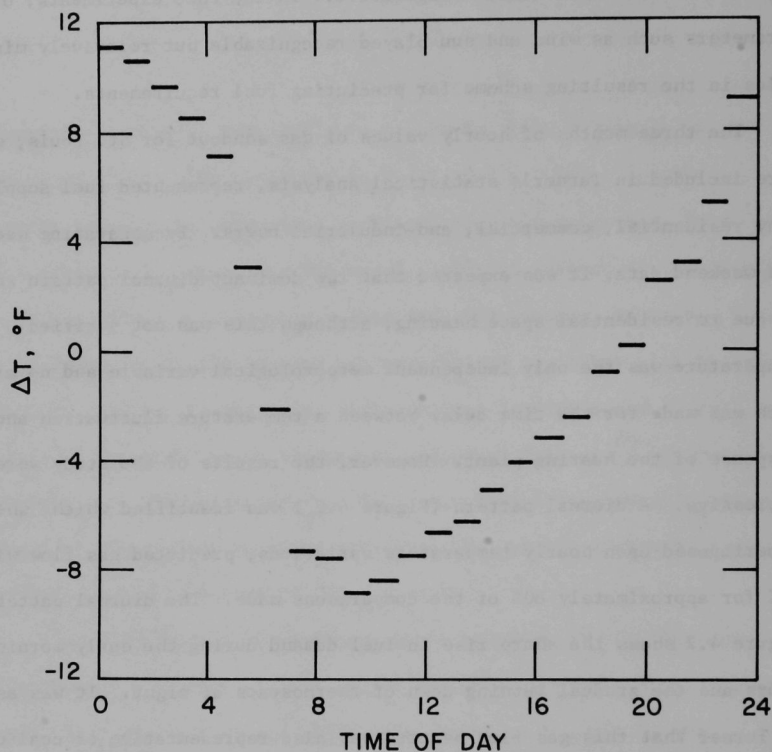
#### 4.4.1 Small-to-Medium Residential Fuel Use Pattern ( $P_1$ )

Studies by People's Gas, Light and Coke Company (PGLC) of the daily gas consumption of single family residences in Chicago<sup>(17)</sup> and by Turner<sup>(18)</sup> on

hourly gas consumption in St. Louis substantiate the very strong coupling between fuel use and outside temperature. In the PGLC experiments, other parameters such as wind and sun played recognizable but relatively minor roles in the resulting scheme for predicting fuel requirements.

The three months of hourly values of gas sendout for St. Louis, which were included in Turner's statistical analysis, represented fuel supply to many residential, commercial, and industrial users. By separating weekday and weekend data, it was expected that the dominant diurnal pattern would be due to residential space heating, although this was not verified. Hourly temperature was the only independent meteorological variable and no allowance was made for the time delay between a temperature fluctuation and the response of the heating plant. However, the results of the study were impressive. A diurnal pattern (Figure 4.2) was identified which, when superimposed upon hourly temperature variations, predicted gas flow within 10% for approximately 80% of the comparisons made. The diurnal pattern of Figure 4.2 shows the sharp rise in fuel demand during the early morning hours and the gradual turning down of thermostats at night. It was assumed by Turner that this gas flow pattern was also representative of coal use for residential heating, but it is not clear how significantly industrial and commercial users influence the gas flow.

The results of Turner's detailed gas study could easily be incorporated in the Chicago model instead of the "janitor function" proposed in the first quarterly report. However for automatic, stoker fed, low pressure heating plants, the diurnal pattern will probably be uniform during the waking hours and turn off rather sharply at 2200 or 2300. This is partly substantiated



112-9722

Fig. 4.2 Diurnal Fuel Use Pattern, Independent of Temperature.  $\Delta T$  is a Correction Factor to a Linear Fuel Use vs. Temperature Equation,  

$$FU = C_0 - C_1 (T + \Delta T)$$

Thus  $\Delta T > 0$  Implies a Higher Effective Temperature and Therefore a Lower Fuel Use. (Turner, St. Louis (4))

by the University of Chicago fuel use data which shows approximately uniform consumption rates during the day, and is in contrast to the function in Figure 4.2, which drops almost linearly from 0900 to 2000.

#### Building Instrumentation Experiments

To resolve these discrepancies and substantiate any proposed "janitor function", a limited experimental study has been initiated in which two Hyde Park buildings have been instrumented to determine hourly coal consumption. The six flat at 5533-35 S. Blackstone and a court-type four story apartment building with 80 2-3 room units at 5316 S. Dorchester are both managed by University Realty Management Corporation representing the University of Chicago. The stoker in each building is monitored by an Esterline-Angus, clock-wound, pen-recording voltmeter connected in parallel with the stoker relay. The graph paper, which runs at about four inches per hour, can be read to within several minutes to determine the number of minutes of coal stoking per hour. The stoker in the larger building has three speeds ( $1/3$ ,  $2/3$ , and full) which are selected manually by the janitor. He has agreed to note each speed change on our recording paper. This data can then be compared to hourly variations in temperature, wind speed and insolation as well as time delays for each of these independent variables.

The instruments were installed in mid-March, 1968. Only about two weeks of useful data, as yet unprocessed, were gathered because of instrument failures such as a defective escapement mechanism and clogged capillary pens. During the next heating season it seems worthwhile to

continue the experiments with improved instrumentation. Inexpensive (\$100.00@) event recorders are available with 110v electric motors and pressure sensitive paper which needs changing only once a month. This compares favorably with the weekly servicing requirements of the meters presently being used.

The limited scale of the experiment is governed in part by the availability of instruments and primarily by the task of reducing the data. One possibility for the winter 1968 tests would involve moving the meters to two new buildings in January. This would make the study more representative, but still, from a statistical viewpoint, the sample is insufficient. Nevertheless, it is advantageous to have some evaluation, however limited, of the diurnal pattern, our estimate of which up until now has evolved purely from interviews with janitors.

#### 4.4.2 High Pressure Steam System

Very large steam heated structures which account for slightly under 20% of the total annual  $\text{SO}_2$  emissions fall into two general categories: residential structures such as apartment complexes operated by the Chicago Housing Authority and "commercial" institutions such as hospitals, and universities<sup>(1)</sup>. Although the functions of these two classes of buildings are quite different, they may be expected to have similar fuel use patterns, since all the heating plants operate on a 24 hour basis, and the users generally are not prone to economize by significantly reducing the night-time heating demands. It is anticipated, therefore, that fuel use in these buildings will closely follow a linear relationship with hourly

temperature, the only complication being a time lag consistent with the thermal-inertia of the large buildings.

Daily fuel consumption figures have been obtained for the University of Chicago (UC), Illinois Institute of Technology (IIT), and the Stateway apartment buildings (STWY) of the Chicago Housing Authority. Figures 4.3 and 4.4 show the daily data for December 1966 and January 1967 for IIT and Stateway. Table 4.1 lists results of a statistical study based on the regression equation:

$$F_n = C_0 + C_1 DD_n + C_2 \cdot S_n + C_3 \cdot DDY_n + C_4 \cdot W_n$$

$$n = 1, \dots, N$$
(2)

where

$$F_n = \left[ \begin{array}{c} \text{fuel fraction} \\ \text{for day } n \end{array} \right] \equiv \left[ \begin{array}{c} \text{Fuel Used} \end{array} \right]_n \bigg/ \sum_{j=1}^N \left[ \begin{array}{c} \text{Fuel Used} \end{array} \right]_j$$

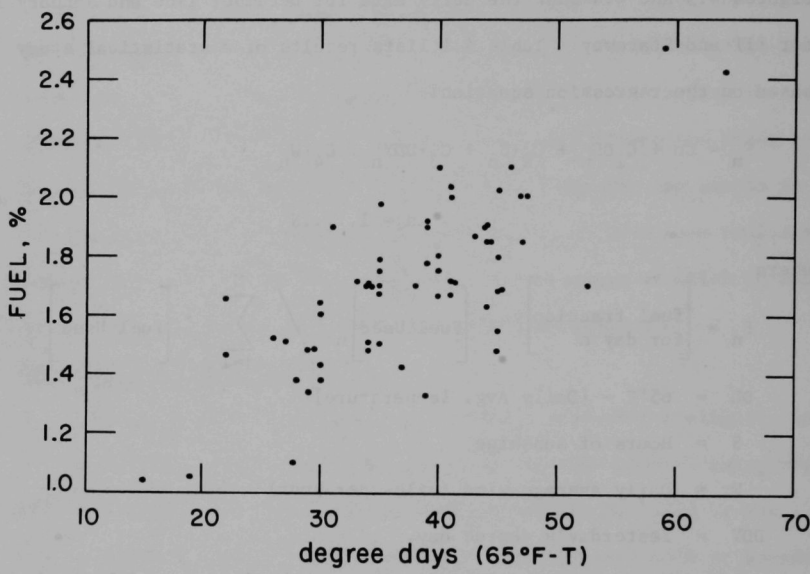
$$DD = 65^\circ\text{F} - [\text{Daily Avg. Temperature}]$$

$$S = \text{Hours of sunshine}$$

$$W = \text{Daily average wind (miles per hour)}$$

$$DDY = \text{Yesterday's degree day.}$$

Although the regression coefficients themselves are of limited value in actually determining the hourly high pressure steam pattern  $P_2$ , several useful conclusions arise: 1) The base load is almost 50% of the total fuel consumption at  $0^\circ\text{F}$ , 2) Although not shown here, there is no noticeable influence of week-ends or holidays on fuel consumption, 3) The magnitudes of the coefficients for all variables other than degree days indicate that the only significant variable is temperature. This is also substantiated by



112-9723

Fig. 4.3 Fuel Use Data for Illinois Institute of Technology Dec 1966 and Jan 1967

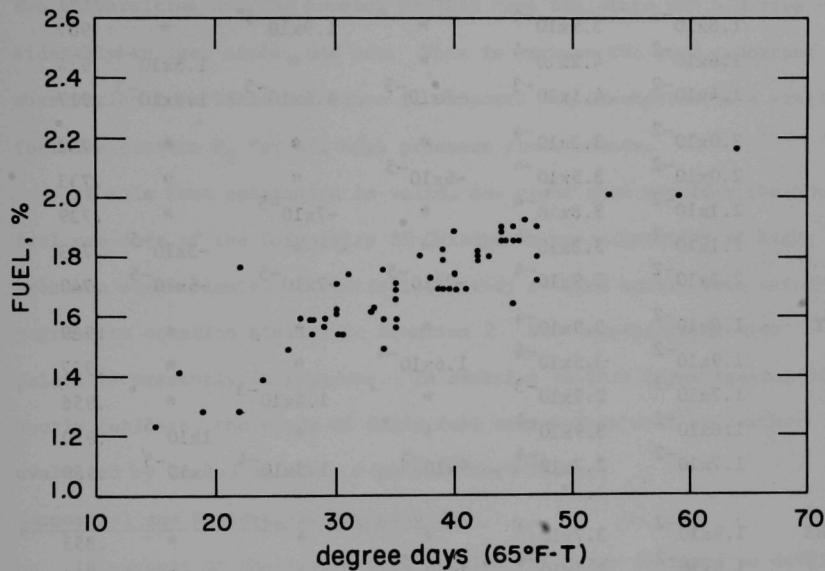


TABLE 4.1 Fuel use study for high pressure steam plants.

December 1966

Sources	Regression Coefficients (Eq. 2)					Multiple Regression Coefficient
	$C_0$	$C_1$	$C_2$	$C_3$	$C_4$	
UC	$1.8 \times 10^{-2}$	$4.0 \times 10^{-4}$	*	*	*	.907
	$1.8 \times 10^{-2}$	$4.1 \times 10^{-3}$	$-3 \times 10^{-5}$	*	*	.907
	$1.8 \times 10^{-2}$	$3.9 \times 10^{-4}$	*	$1.9 \times 10^{-5}$	*	.907
	$1.6 \times 10^{-2}$	$4.2 \times 10^{-4}$	*	*	$1.5 \times 10^{-4}$	.914
	$1.4 \times 10^{-2}$	$4.1 \times 10^{-3}$	$-8 \times 10^{-5}$	$4.4 \times 10^{-5}$	$1.8 \times 10^{-3}$	.917
IIT	$2.0 \times 10^{-2}$	$3.3 \times 10^{-4}$	*	*	*	.732
	$2.0 \times 10^{-2}$	$3.5 \times 10^{-4}$	$-6 \times 10^{-5}$	*	*	.733
	$2.1 \times 10^{-2}$	$3.8 \times 10^{-4}$	*	$-7 \times 10^{-5}$	*	.739
	$2.1 \times 10^{-2}$	$3.3 \times 10^{-4}$	*	*	$-3 \times 10^{-5}$	.733
	$2.2 \times 10^{-2}$	$3.9 \times 10^{-4}$	$-2 \times 10^{-5}$	$-7 \times 10^{-5}$	$-6 \times 10^{-5}$	.740
STWY	$1.8 \times 10^{-2}$	$3.9 \times 10^{-4}$	*	*	*	.930
	$1.9 \times 10^{-2}$	$3.5 \times 10^{-4}$	$1.6 \times 10^{-4}$	*	*	.937
	$1.7 \times 10^{-2}$	$2.9 \times 10^{-3}$	*	$1.4 \times 10^{-3}$	*	.956
	$1.8 \times 10^{-2}$	$3.9 \times 10^{-4}$	*	*	$1 \times 10^{-5}$	.930
	$1.7 \times 10^{-2}$	$2.7 \times 10^{-4}$	$9 \times 10^{-5}$	$1.3 \times 10^{-4}$	$6 \times 10^{-5}$	.959
ALL THREE	$1.9 \times 10^{-2}$	$3.7 \times 10^{-4}$	*	*	*	.853
	$1.9 \times 10^{-2}$	$3.7 \times 10^{-4}$	$2 \times 10^{-5}$	*	*	.853
	$1.9 \times 10^{-2}$	$3.5 \times 10^{-4}$	*	$3 \times 10^{-5}$	*	.854
	$1.8 \times 10^{-2}$	$3.8 \times 10^{-4}$	*	*	$5 \times 10^{-5}$	.854
	$1.8 \times 10^{-2}$	$3.7 \times 10^{-4}$	$-1 \times 10^{-6}$	$4 \times 10^{-5}$	$6 \times 10^{-5}$	.855

\* Corresponding variable not included in the regression analysis

the negligible increase in the multiple regression coefficient as these variables are selectively introduced. The exception is Stateway which alone shows a strong correlation with yesterday's degree day. (Apparently people are slow in reacting to changes in weather) 4) The regression coefficients  $C_0$  and  $C_1$  are similar in magnitude for each source although the two universities and the housing project have buildings which differ considerably in age, style, and use. This is perhaps the most important observation from Table 4.1 since it supports the assumption of a single fuel use pattern  $P_2$  for all high pressure steam plants.

If this last conclusion is valid, one might then consider the hourly fuel use data of the University of Chicago as representative of high pressure steam plants. A statistical study of this hourly data using a regression equation similar to Equation 2 but incorporating time delays is presently in progress. In addition to this investigation of hourly fuel use, the study of daily fuel consumption will be further evaluated by including other months as test data.

#### 4.4.3 Commercial and Residential Emission Data

In support of the statistical studies which are designed to develop correlations for the simulation of commercial and residential space heating fuel use patterns, fuel consumption data for eleven major residential heating plants and six major commercial sources was acquired. Appendix I summarizes the stack characteristics of each of these large, space heating facilities.

Information concerning the location of tall stacks on elementary and high schools throughout Chicago has been acquired. These relatively small SO<sub>2</sub> sources are not included as discrete emitters in the inventory file, but they have a disturbing tendency to cluster in areas adjacent to the TAM receptor sites, and could serve to compromise the statistical study of major SO<sub>2</sub> sources which they would tend to mask.

#### 4.4.4 Chicago Source Coordinate System

On the basis of the grid system defined as part of the SO<sub>2</sub> Transport Map<sup>(1)</sup>, code numbers and coordinates have been assigned to all major SO<sub>2</sub> sources and meteorological and TAM data acquisition stations involved in the dispersion model development study. This aggregate of identifying code numbers and coordinates has been combined with a computer subroutine designed to calculate the downwind and crosswind intervals between any combination of sources and/or stations by performing an appropriate rotation of the coordinate system to correspond to the prevailing wind direction. This algorithm will be of general use in both the statistical dispersion analyses and the optimal abatement strategy studies. The identifying code and coordinates for each source and station are shown in Appendix II of this report.

## CHICAGO AIR POLLUTION DISPERSION MODEL

### 5.0 Applied Programming

F. Clark

A. Kennedy

J. Gregory

## 5.0 Applied Programming

Significant progress was made during this quarter in providing the computational tools necessary for the processing and analysis of air pollution data. Milestones achieved include the development of the master information system; a TAM network data processing program; programs to process Commonwealth Edison (CECO) emission data, and the initiation of the development of an industrial plant simulation program (PLANTSIM). Each of these programs is described in detail below.

The St. Louis dispersion model development, using Argonne's system 360-75 computer, was completed during this quarter (see Section 2.3).

### 5.1 Air Pollution Master Information System

The Air Pollution Master Information System has evolved as a collection of processing programs to accomplish the following tasks<sup>\*</sup>:

- 1) data file preparation;
- 2) data retrieval and search;
- 3) regression analysis;
- 4) data display.

The logical flow of information through the system is represented in figures 5.1, 5.2, and 5.3. The programs to accomplish the above tasks are discussed in turn below. First, however, it is appropriate to describe the data file format.

#### 5.1.1 Data File Format

Data records in the master file are blocked and retrieved by date. That is, for each day proceeding sequentially from January 1, 1966,

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<sup>\*</sup>The system development has proceeded essentially as outlined in the first review meeting.

DATE: 66/01/01

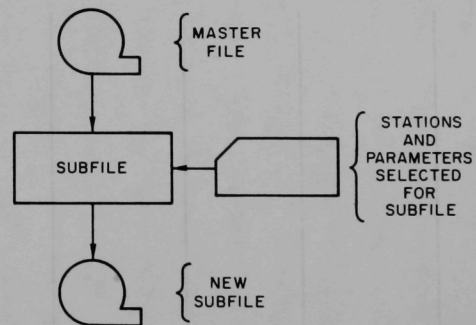
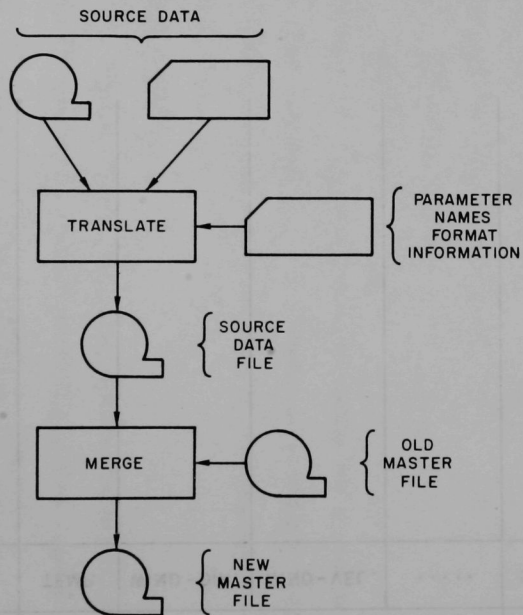
TIME	MIDWAY				U-OF-C				
HOUR	TEMP.	WIND - DIR.	WIND - VEL.	.....	SO <sub>2</sub> - S1	TEMP. - S1	SO <sub>2</sub> - S2	TEMP. - S2	.....
1									
2									
3									
.									
.									
.									
.									
23									
24									

112-9725

Fig. 5.1 Sample Master File Record Format

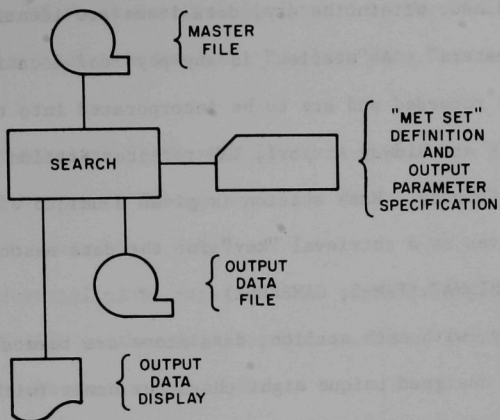
## DATA TRANSLATION AND MASTER FILE UPDATE

## SUBFILE GENERATION



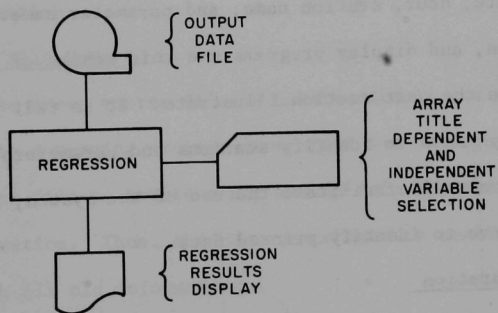
112-9726

Fig. 5.2 Data File Preparation



112-9727

Fig. 5.3 Data Retrieval and Search



112-9728

Fig. 5.4 Regression Analysis

twenty-four hours "worth" of data items are stored in the record for that date. The format of the record is shown in figure 5.4.

For each hour within the day, data items are identified by "station parameters". A "station" is any physical location where data items are recorded and are to be incorporated into the master file. Examples are Midway Airport, TAM receptor Station 3, and Campbell Soup Company. Each station is given a unique eight character name which serves as a retrieval "key" for the data associated with that station (e.g. MIDWAY, TAM-3, CAMPBELL).

Similarly, with each station, data items are termed "parameters" which are also assigned unique eight character names (within each station). Typical examples are the temperature at Midway Airport (TEMP), wind direction at TAM station 3 (WIND-DIR), and SO<sub>2</sub> emission from Campbell's Soup Company (SO2-TOT).

Thus, every data item on the master file can be accessed by specifying the correct date, hour, station name, and parameter name. The data retrieval, regression, and display programs use this scheme of identification, as the examples in the next section illustrate. It is felt that the use of descriptive key names to identify stations and parameters (as opposed to a numbering scheme) will facilitate the use of the system, reduce input errors, and serve to identify printed data.

#### 5.1.2 Data File Preparation

##### Data Translation

Data comes to Argonne from many different sources in a format specified by the processing program that produced it. The first stage of

file preparation is to create a "preprocessing" program to translate this data into the master file format.

A series of these routines (indicated by the TRANSLATE box in figure 5.2) has been generated to translate data for the following data sources:

- 1) TAM stations (1 through 8);
- 2) University of Chicago emission data;
- 3) CECO power plant data;
- 4) Industrial plant emission data created by the PLANTSIM program;
- 5) Ashville weather data for Midway, O'Hare, Meigs, and Glenview Airport weather stations.

Each additional data source will, in general, require one of these preprocessing programs. It should be mentioned, however, that these programs have been standardized to the extent that each new program is created from a previous one by merely inserting new parameter names and format information.

#### Master File Update

Once the above source file is constructed in the master file format, it is fed into a merging program (the MERGE box in figure 5.2) along with the old master file to create a new master file updated with the new source information. Thus, the new source data is available for processing together with all old information.

## Subfile Generation

It is readily obvious that, as the volume of data grows in the master file, the processing time to handle this data increases rapidly. Since the usual procedure will be to concentrate on a subset of the master file for a sequence of processing runs, a program has been written (the SUBFILE box in figure 5.2) to extract the desired subset and place it on a separate "subfile".

The input format to the SUBFILE program is as follows:

```

SUBFIL INPUT DESCRIPTION (NOTE: INFORMATION ENCLOSED IN PARENS IS
                           EXPLANATORY ONLY AND SHOULD NOT BE PUNCHED)
TITLE      ( 80 CHARACTERS - DESCRIPTIVE INFORMATION)
OUT_STATIONS=NO; (NO=NUMBER OF OUT STATIONS)
-----
(OUT STATION DEFINITION CARDS - ONE SET PER STATION)
STATION='NAME ' PARAMS=NP; (NP= NUMBER OF OUTPUT PARAMTETERS)
(OUTPUT PARAMETER DEFINITION CARDS - ONE CARD PER PARAMETER )
-----
PARAM='NAME ' ;
END      (THIS CARD MUST FOLLOW EACH CASE)
STOP    (THIS CARD MUST FOLLOW THE RUN)
-----

```

A sample input deck might be

```

SAMPLE SUBFILE
OUT STATIONS=2;
STATION='MIDWAY'  PARAMS=3;
-----
PARAM='TEMP';
PARAM='WIND_DIR';
PARAM='WIND_VEL';
-----
STATION='U_OF_C'  PARAMS=2;
PARAM='S02_S1';
PARAM='S02_S2';
-----
END
STOP

```

This example would select from the master file the parameters temperature (TEMP), wind direction (WIND-DIR), and wind speed (WIND-VEL) for

Midway Airport and the SO<sub>2</sub> emission data for stacks one (SO2-S1) and two (SO2-S2) of the University of Chicago heating plant and place them on a separate file.

### 5.1.3 Data Retrieval and Search

A search program (the SEARCH box in figure 5.3) has been written to accept a "MET SET"\* definition and search the master file for corresponding output data, which is also specified.

A search of the master file is defined by input of the following information:

- 1) a title which serves to identify this output data on the output data file;
- 2) a set of data limits which select days of interest;
- 3) a set of hour limits which select the hours of interest for each day;
- 4) a set of selected MET Stations and MET parameters for each station;
- 5) a set of "band limits" for each MET parameter which delimits the search on that parameter;
- 6) a set of selected output stations and output parameters for each station with a time delay for each parameter.

---

\* See ANL/ES-CC-001, "Diffusion Analysis", Chicago Air Pollution System Model, First Quarterly Progress Report, February 1968. The term "MET SET" as originally defined referred to searching on MET parameters. However, as far as the search program is concerned, any parameter may be included in the "MET SET".

Given the above information, the program proceeds to search the master data file in the following manner:

- 1) for each day and hour of interest, a search of the specified MET SET is made to determine if all MET parameters lie within some band;
- 2) if some MET parameter does not lie within a band, the search proceeds to the next day and hour;
- 3) if all MET parameters lie within some band, (or a MET SET was not specified) the corresponding output parameter values for that day and hour (minus the time delay) are recorded on the output data file;
- 4) when the search of the master file is complete, the resulting output data is displayed on the printer;
- 5) Continue to the next case.

The result of a sequence of such search passes through the master file is then a corresponding set of output data arrays (identified by a unique title) on the output data file which can in turn be fed into the regression program as shown in figure 5.4.

The input format to the SEARCH program is as follows:

SEARCH INPUT DESCRIPTION (NOTE: INFORMATION ENCLOSED IN PARENS IS  
EXPLANATORY ONLY AND SHOULD NOT BE PUNCHED)

TITLE	( 80 CHARACTERS - USED TO IDENTIFY ARRAY ON OUTPUT TAPE)
DATE LIMITS=ND:	(ND=NUMBER OF DATE LIMITS)
(DATE LIMIT CARDS - EACH PAIR SEPARATED BY AT LEAST ONE BLANK )	
'YL/ML/DL','YU/MU/DU'	('LOWER DATE LIMIT','UPPER DATE LIMIT')
HOUR LIMITS=NH:	(NH=NUMBER OF HOUR LIMITS)
(HOUR LIMIT CARDS - EACH PAIR SEPARATED BY AT LEAST ONE BLANK )	
HL,HU	(LOWER HOUR LIMIT,UPPER HOUR LIMIT)
MET STATIONS=NM:	(NM=NUMBER OF MET STATIONS)
(MET STATION DEFINITION CARDS - ONE SET PER STATION)	
STATION='NAME'	PARAMS=NP; (NP= NUMBER OF SEARCH PARAMETERS)
(SEARCH PARAMETER DEFINITION CARDS - ONE SET PER PARAMETER)	
PARAM='NAME'	BANDS=NB; (NB=NUMBER OF BAND LIMITS FOR THIS PARAMETER)
(BAND LIMIT CARDS - EACH PAIR SEPARATED BY AT LEAST ONE BLANK )	
BL,BU	(LOWER BAND LIMIT,UPPER BAND LIMIT)
OUT STATIONS=NO:	(NO=NUMBER OF OUT STATIONS)
(OUT STATION DEFINITION CARDS - ONE SET PER STATION)	
STATION='NAME'	PARAMS=NP; (NP= NUMBER OF OUTPUT PARAMETERS)
(OUTPUT PARAMETER DEFINITION CARDS - ONE CARD PER PARAMETER )	
PARAM='NAME'	DELAY=TD; (TD= TIME DELAY IN HOURS UP TO 24 MAX)
END	(THIS CARD MUST FOLLOW EACH CASE)
STOP	(THIS CARD MUST FOLLOW THE RUN)

A sample input deck might be

SAMPLE INPUT 1  
DATE LIMITS=1;

'66/01/01','66/01/10'	
HOUR LIMITS=1;	6, 18
MET STATIONS=1;	
STATION='MIDWAY'	PARAMS=2;
PARAM='WIND_VEL'	BANDS=1; 5, 10
PARAM='WIND_DIR'	BANDS=1; 200, 250
OUT STATIONS=2;	
STATION='MIDWAY'	PARAMS=3;
PARAM='WIND_DIR';	
PARAM='WIND_VEL';	
PARAM='TEMP'	DELAY=1;
STATION='U_OF_C'	PARAMS=2;
PARAM='S02_S1'	DELAY=2;
PARAM='S02_S2'	DELAY=2;
END	
STOP	

This example searches the master file between the dates 66/01/01 and 66/01/10 and between the hours 6 and 18 for each day. For each hour of interest, the wind speed (WIND-VEL) must be between 5 and 10 knots and the wind direction (WIND-DIR) must be between 200 and 250 degrees. If these conditions are satisfied, the values of the parameters wind direction, wind speed, and temperature (TEMP minus a one hour time delay) at Midway Airport, and SO<sub>2</sub> emissions data for stacks one (SO2-S1) minus a two hour time delay) and two (SO2-S2 minus a two hour time delay) from the University of Chicago heating plant are placed on the output data file. The printed results of this search are shown below.

#### SAMPLE INPUT I

	MIDWAY TEMP	MIDWAY WIND DIR	MIDWAY WIND VEL	U OF C SO2 S1	U OF C SO2 S2
66/01/03 6	24.000	240.000	10.000	396.410	349.480
66/01/03 14	33.000	240.000	10.000	492.610	380.120
66/01/03 16	37.000	220.000	9.000	498.150	386.200
66/01/03 17	37.000	220.000	10.000	489.350	377.080
66/01/04 10	29.000	210.000	10.000	605.290	331.120
66/01/05 15	45.000	210.000	6.000	454.620	297.190
66/01/05 16	47.000	210.000	6.000	434.540	313.700
66/01/05 17	48.000	200.000	6.000	420.650	290.590
66/01/08 13	12.000	220.000	7.000	719.220	396.380
66/01/08 15	18.000	230.000	10.000	658.240	377.950
66/01/08 17	18.000	220.000	7.000	644.820	347.220

#### 5.1.4 Regression Analysis

A regression analysis program has been written (the REGRESSION box in figure 5.4) which operates on the data selected by the search program. The input title to the regression program must agree with that of the desired data array on the output file for retrieval purposes. The dependent and independent variables are then selected by inputting the proper

station and parameter names. The input format to the REGRESSION program is as follows:

REGRES INPUT DESCRIPTION (NOTE: INFORMATION ENCLOSED IN PARENS IS EXPLANATORY ONLY AND SHOULD NOT BE PUNCHED)

TITLE ( 80 CHARACTERS - USED TO RETRIEVE ARRAY ON OUTPUT TAPE)		
(DEPENDENT VARIABLE CARD - ONLY ONE PER CASE)		
TYPE='DEP'	STATION='NAME_____'	PARAM='NAME_____';
(INDEPENDENT VARIABLE CARDS)		
TYPE='IND'	STATION='NAME_____'	PARAM='NAME_____';
END (THIS CARD MUST FOLLOW EACH CASE)		
STOP (THIS CARD MUST FOLLOW THE RUN)		

A sample input deck might be

SAMPLE INPUT 1		
TYPE='IND'	STATION='MIDWAY'	PARAM='TEMP';
TYPE='IND'	STATION='MIDWAY'	PARAM='WIND VEL';
TYPE='DEP'	STATION='U_OF_C'	PARAM='S02_S2';
END		
STOP		

This example searches the output file for the array titled "SAMPLE INPUT 1" produced by the search run shown in the previous section. The parameter SO<sub>2</sub> emission data from stack two (S02-S2) for the University of Chicago heating plant is selected as the dependent variable, and the parameters temperature (TEMP) and wind speed (WIND-VEL) at Midway Airport are selected as the independent variables. The regression analysis results for this set of data are shown on the following page:

## REGRESSION ANALYSIS RESULTS

STATION	PARAMETER	VAR NO	REG COEF	S.D. REG COEF
MIDWAY	TEMP	1	-0.1479165E 01	0.7283614E 00
MIDWAY	WIND_VEL	3	9.8626674E 01	0.4927691E 01

DEPENDENT VARIABLE				
U_OF_C	S02_S2	5	0.3251589E 03	0.2674812E 02

MULTIPLE CORRELATION COEFFICIENT= 0.7666295E 00

SUM OF SQUARES ATTRIBUTABLE TO REGRESSION(SSAR)= 0.8159359E 04

DEGREES OF FREEDOM ASSOCIATED WITH SSAR= 0.2000000E 01

MEAN SQUARE OF SSAR= 0.4079680E 04

SUM OF SQUARES OF DEVIATIONS FROM REGRESSION(SSDR)= 0.5723699E 04

DEGREES OF FREEDOM ASSOCIATED WITH SSDR= 0.8000000E 01

MEAN SQUARE OF SSDR= 0.7154624E 03

F-VALUE= 0.5702158E 01

5.1.5 Data Display

In addition to the above printed data, a program has been written (PRINT) to search the master file on selected dates and print parameters for specified stations.

The input format for the PRINT program is as follows:

PRINT INPUT DESCRIPTION (NOTE: INFORMATION ENCLOSED IN PARENS IS EXPLANATORY ONLY AND SHOULD NOT BE PUNCHED)

TITLE	( 80 CHARACTERS - DESCRIPTIVE INFORMATION)
DATE LIMITS=NO:	(NO=NUMBER OF DATE LIMITS)
(DATE LIMIT CARDS - EACH PAIR SEPARATED BY AT LEAST ONE BLANK )	
'YL/ML/DL','YU/MU/DU'	('LOWER DATE LIMIT','UPPER DATE LIMIT')
OUT STATIONS=NO:	(NO=NUMBER OF OUT STATIONS)
(OUT STATION DEFINITION CARDS - ONE SET PER STATION)	
STATION=NAME	PARAMS=NP: (NP=NUMBER OF OUTPUT PARAMTETERS)
(OUTPUT PARAMETER DEFINITION CARDS - ONE CARD PER PARAMETER )	
PARAM=NAME	DELAY=TD: (TD= TIME DELAY IN HOURS UP TO 24 MAX)
END	(THIS CARD MUST FOLLOW EACH CASE)
STOP	(THIS CARD MUST FOLLOW THE RUN)

A sample input deck might be

```

SAMPLE INPUT
DATE LIMITS=1;
'66/01/01','66/01/10'
OUT STATIONS=2;
STATION='MIDWAY' PARAMS=3;
PARAM='TEMP' DELAY=1;
PARAM='WIND_DIR';
PARAM='WIND_VEL';
STATION='U_OF_C' PARAMS=2;
PARAM='SO2_S1' DELAY=2;
PARAM='SO2_S2' DELAY=2;
END
STOP

```

This example will print the temperature (minus a one hour delay), wind direction, and wind speed at Midway Airport and the SO<sub>2</sub> emission data for stacks one and two (minus a two hour delay) for the University of Chicago heating plant for the first ten days of January 1966. The printed output is shown below.

1      40.000          0.0          0.0          375.080          337.570

SAMPLE INPUT  
DATE:66/01/01

HOUR	MIDWAY TEMP	MIDWAY WIND_DIR	MIDWAY WIND_VEL	U_OF_C SO2_S1	U_OF_C SO2_S2
1	40.000	0.0	0.0	375.080	337.570
2	35.000	0.0	0.0	325.260	327.100
3	34.000	300.000	4.000	280.460	238.620
4	33.000	330.000	4.000	289.230	238.620
5	79.000	360.000	4.000	283.390	229.070
6	31.000	350.000	3.000	286.310	238.620
7	30.000	350.000	6.000	315.520	257.710
8	30.000	360.000	5.000	327.210	262.480
9	30.000	360.000	5.000	362.270	269.640
10	29.000	60.000	5.000	368.110	298.270
11	33.000	50.000	11.000	415.610	365.510
12	37.000	70.000	10.000	389.640	362.490
13	39.000	50.000	14.000	370.160	362.490
14	41.000	50.000	13.000	357.170	350.410
15	42.000	60.000	14.000	353.920	338.330
16	42.000	50.000	13.000	344.180	335.310
17	41.000	60.000	12.000	344.180	332.290
18	39.000	50.000	13.000	366.910	338.330
19	38.000	50.000	12.000	339.910	308.790
20	37.000	60.000	15.000	363.350	327.100
21	39.000	50.000	12.000	369.220	329.720
22	40.000	60.000	14.000	366.290	332.340
23	41.000	60.000	13.000	375.080	332.340
24	40.000	70.000	15.000	369.220	332.340

Although graphic display capability is not currently available, it should not be difficult to incorporate such a feature into this program.

#### 5.1.6 Summary of System Capabilities

The master information system has been designed to handle future needs and expansion as much as possible. With this in mind, a summary of the system capabilities is as follows:

- 1) new data sources (regardless of format) are incorporated into the master file with a minimum of effort;
- 2) the system can operate on any combination of stations and parameters for the purposes of
  - a) creating data files,
  - b) searching data files,
  - c) regression analysis,
  - d) data display,
- 3) extensions of system capabilities (such as new analysis routines or a graphical display package) may be easily accomplished;
- 4) any combination of current (or new) programs may be combined into a one pass operation.

#### 5.2 TAM Network Data

The DAPC has now furnished data for the period January 1, 1966 through December 31, 1967. A significant amount of editing of the data has been done for both the benefit of the Argonne program and the biomedical study program currently in progress at the Illinois Research

Hospital. This editing is still in progress and completion is anticipated very shortly. The editing process and those computer programs which use the TAM data are described below.

#### Program SHAPEUP

This is a FORTRAN program written for execution on the CDC 3600 computer. It is designed to produce, from the source TAM data, a data set with one reading per fifteen minute period per station.

It was necessary to insert data items as well as remove duplicates. For the most part, only time and station identification was inserted, since previously missing readings were a result of no readings having been taken. In these instances, missing data were indicated by the insertion of non-numeric quantities for  $\text{SO}_2$ , wind speed and direction. It has been suggested, however, that numeric values (interpreted as were the non-numeric values) be used throughout so as to enable more users to employ the SHAPEUP results arithmetically. A problem peculiar to high-level language scientific programming is the difficulty, in general, of handling character strings which consist of both arithmetic and non-numeric values. The use of numeric values throughout make stored data considerably more manageable for the programmer and user, hence a re-editing to provide this type of file is in progress.

Manual editing of the TAM data requiring "plugs" for apparently bad readings has been completed. SHAPEUP enables the user to overlay the  $\text{SO}_2$ , wind speed and direction readings for a fifteen minute period for any station and to insert legitimate readings where no observations are recorded.

### Hourly Averaging

The hourly averages of the data contained on the TAM tape were regenerated following processing in program SHAPEUP.

### Six and Twelve Hour Averages

For statistical studies at Argonne, six-hour averages were produced from the hourly averages (see Section 2.1). These averages were for  $\text{SO}_2$  concentration, wind speed and direction. A second program was written at the request of the Chicago DAPC to produce twelve-hour averages for use by biomedical research workers at the Illinois Research Hospital. This file contained only time and  $\text{SO}_2$  concentration data. Both the six-hour and twelve-hour processing programs were prepared for use with relatively unedited data, but will be run using the final, edited version of the TAM tape data file.

### Merging and Listing

The relatively simple task of merging two like data sets and listing the result is greatly complicated by the task of handling massive quantities of data. The two years of TAM data available consist of approximately half a million readings and exist in blocked form on one reel of tape. The merging of the 1966 and the 1967 data was accomplished by the use of a simple COBOL program on the IBM 360/75. Since the merge operation precedes the SHAPEUP process, nothing is done during the merging process insofar as editing of the data is concerned. Problems associated with merging were more mechanical than computational in nature, because the tapes provided

were considered marginal with regard to storage effectiveness and proved to be rather difficult to copy, or even read, in some instances. Problems of this nature were anticipated, however, and no safeguards can be employed to prevent them.

A FORTRAN program was written to list the complete edited version of the TAM tape in a readable form. This program too, must be run with a version of the TAM tape consisting purely of numeric data.

#### Anticipated Additions

A program is now being prepared which will facilitate the determination of the validity of  $\text{SO}_2$  concentration and wind data. In general, it is true that a change from one fifteen minute period to the next should not produce an increase or decrease of  $\text{SO}_2$  concentration of more than about .15 ppm or a change in wind direction of more than  $60^\circ$ . It is a relatively simple matter, from a programming standpoint, to pass through the entire data set and display suspicious or anomalous data for visual inspection and future "plugging". In view of the fact that a preliminary visual inspection of the raw data has revealed the existence of a fairly significant number of anomalous data points in the TAM file, it is appropriate to conduct such a computerized search and inspection to insure that spurious data will be eliminated from the statistical studies.

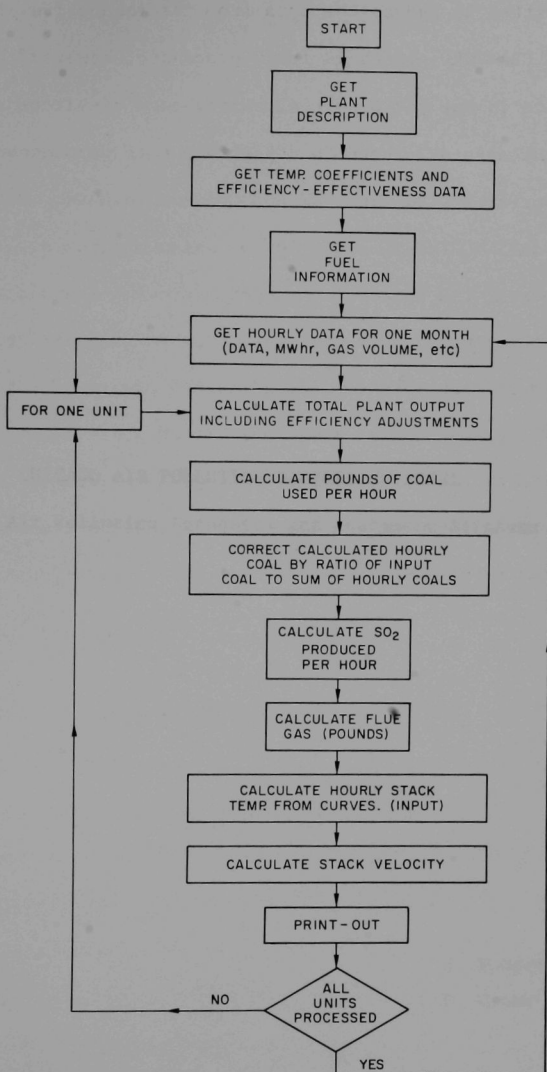
### 5.3 Commonwealth Edison Processing Codes

Fuel consumption, fuel type, boiler and turbine efficiency data, physical plant characteristics, etc., have been received for four of the six Commonwealth Edison Plants serving the Chicago area. These are the

FISK, CRAWFORD, RIDGELAND and NORTHWEST Plants. Data processing programs have been written to reduce the data from the respective plants. Data for the FISK and CRAWFORD plants is fully processed; however the processing of RIDGELAND data is not yet complete, partly as a result of a delay in receipt of the data at Argonne and partly due to unforeseen data handling problems associated with the FISK and CRAWFORD plants. Data from the relatively small NORTHWEST plant is now being processed.

In general, the processing programs are the same; the basic differences being the input/output portions. Naturally, characteristics peculiar to an individual plant are considered in the program for that plant. The existence of (in some cases extensive) differences in the plants motivated the production of a separate computer program for each.

The general flow diagram (Figure 5.5) depicts the overall Edison plant computer program effort.



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Fig. 5.5 General Commonwealth Edison Flow Diagram  
(Fisk, Crawford, and Ridgeland)



## CHICAGO AIR POLLUTION DISPERSION MODEL

### 6.0 Air Pollution Economics and Abatement Strategy

J. Roberts

E. Croke

## 6.0 Optimal Abatement Model

### 6.1 Evaluation of an SO<sub>2</sub> Dispersion Kernel

#### 6.1.1 Introduction

In support of an operations research study of optimal strategies for pollution abatement, a computer code DAVKERN has been written which couples each Commonwealth Edison power plant with the Lindbloom and Hyde Park TAM Stations. Assuming that each utility is controlled in piecewise constant, two-hour steps, the concentration of SO<sub>2</sub> at either TAM Station at time T can be evaluated as a convolution sum of the products of the piecewise constant, two-hour emissions during the intervals  $(T-\tau-2, T-\tau)$ ,  $\tau \geq 0$  and a discrete transfer function associated with the delay time  $\tau$ .

The transfer function is based on a diffusion kernel similar to one used by Professor Davidson of New York University in his model of SO<sub>2</sub> dispersion over New York City. The function has been evaluated for several wind speeds (0,1,2,3,4, mph) and wind directions (225°, 270°, 315°).

#### 6.1.2 Diffusion Kernel

This section outlines the development, from a point source equation, of the chosen kernel.

##### Model of the SO<sub>2</sub> Puff

For a mean wind  $u$  in the  $x$  direction, with  $y$  and  $z$  representing unbounded crosswind and vertical dimensions, a normal distribution is postulated.

$$\chi(t, t') = \frac{\left\{ Q(t') \exp - \frac{[x-u(t-t')]^2}{2\sigma_{x,i}^2} + \frac{y^2}{2\sigma_{y,i}^2} + \frac{z^2}{2\sigma_{z,i}^2} \right\}}{2^{1/2} \pi^{3/2} \sigma_{x,i}(t-t') \sigma_{y,i}(t-t') \sigma_{z,i}(t-t')} \quad (1)$$

where  $\chi(t, t')$  is the concentration at time  $t$  due to an instantaneous release, at time  $t'$  and position  $(0, 0, 0)$ . The diffusion coefficients  $\sigma_x$ ,  $\sigma_y$ , and  $\sigma_z$  are functions of the delay time  $(t-t')$  and the atmospheric stability class  $i$ .

With the assumptions that a lid of height  $H$  exists over the city and that the concentration of  $SO_2$  is uniform from ground  $z=0$  to height  $z=H$ , the equation becomes

$$\chi(t, t') = \frac{Q(t')}{2\pi H \sigma_x \sigma_y} \exp - \left\{ \frac{[x-u(t-t')]^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2} \right\} \quad (2)$$

where the revised normalization follows from

$$\int_{-\infty}^{\infty} dx e^{-a^2 x^2} = \sqrt{\pi}/a \quad (3)$$

The assumption of complete mixing up to a height of  $H$  is reasonable for pollution incidents and, perhaps more important, simplifies the computer analysis and greatly reduces the amount of tabulated data.

#### Dispersion Parameters

Dispersion coefficients or variances are generally derived from experimental data - smoke or luminous tracer releases over rather uniform terrain, quite unlike urban regions. The data is then fit to a standard plume equation such as

$$\chi = \frac{Q \exp - \left\{ \frac{1}{2} \left( \frac{y^2}{\sigma_y^2} + \frac{H^2}{\sigma_z^2} \right) \right\}}{\pi u \sigma_y \sigma_z} \quad (4)$$

to determine  $\sigma_y$  and  $\sigma_z$ . Note that this equation has no x diffusion and consequently cannot be applied to the zero wind ( $u=0$ ) case.

Although in practice the  $u=0$  case will not persist throughout a pollution incident (nor would any single wind velocity), this case represents a realistic bound on the buildup of  $SO_2$  during stagnation regimes. Turner<sup>(2)</sup> (Nashville) with some subjective modifications presents a set of  $\sigma_y$  curves

$$\sigma_{y,i}(t) = a_{y,i} t^{b_{y,i}}, \quad i = 1, 5 \quad (5)$$

where  $i$  corresponds to one of five classes of atmospheric stability.

Apparently no  $\sigma_x$  functions have been published - probably since the New York model, which is the only one employing this feature, is still under development.

Since by symmetry  $\sigma_x = \sigma_y$  when  $u=0$ , it will be assumed for the limited purposes of this study that  $\sigma_{x,i}(t) = \sigma_{y,i}(t)$  for all  $u$  and that the parameters  $a_{y,i}$  and  $b_{y,i}$  will be those of Turner<sup>(2)</sup>.

Thus

$$\sigma_{x,i}(t) = \sigma_{y,i}(t) = \sigma_i(t) = a_i t^{b_i} \quad (6)$$

where for mks units,

$a = 2$  and  $b = .85$  where  $i = 1$  (extremely unstable)

and

$a = .4$  and  $b = .9$  where  $i = 5$  (extremely stable)

In units of miles and hours,

$a = 1.3$ ,  $b = .85$  for  $i = 1$

and

$$a = .4, b = .9 \text{ for } i = 5.$$

( See Figure 6.1)

### Derivation of the Discrete Transfer Function

Substituting Equation (6) into the puff kernel, Equation (2) one has

$$\chi(t, t') = \frac{Q(t') \exp - \left\{ \frac{[x-u(t-t')]^2 + y^2}{2a_i^2(t-t')} \right\}}{2\pi H a_i^2(t-t')} \quad (7)$$

If emissions  $Q$  are in piecewise constant, two-hour steps, then the concentration (normalized) at time  $t$ ,  $t \geq 2$ , due to a steady emission during the time interval  $(0, 2)$  is

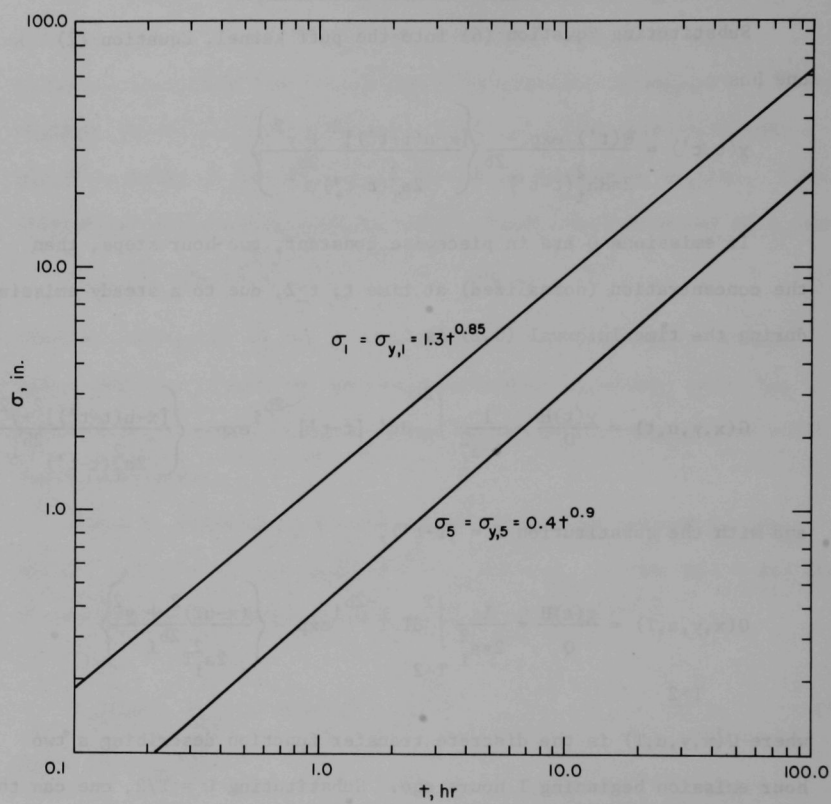
$$G(x, y, u, t) = \frac{\chi(t)H}{Q} = \frac{1}{2\pi a_i^2} \int_0^2 dt' [t-t']^{-2b_i} \exp - \left\{ \frac{[x-u(t-t')]^2 + y^2}{2a_i^2(t-t')} \right\} \quad (8)$$

and with the substitution  $T = (t-t')$ ,

$$G(x, y, u, T) = \frac{\chi(t)H}{Q} = \frac{1}{2\pi a_i^2} \int_{T-2}^T dT T^{-2b_i} \exp - \left\{ \frac{(x-uT)^2 + y^2}{2a_i^2 T} \right\} \quad (9)$$

$$T \geq 2$$

where  $G(x, y, u, T)$  is the discrete transfer function describing a two hour emission beginning  $T$  hours ago. Substituting  $L = T/2$ , one can then introduce the index  $L$  into the transfer function as  $G_L(x, y, u)$ ,  $L \geq 1$ . Let  $Q_n$  be the emission during the two hour interval ending at time  $= 2n$ . The convolution sum which yields the  $SO_2$  concentration for any given piecewise constant past history is therefore



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Fig. 6.1 Cross Wind Dispersion Parameters (Turner (2))

$$\chi(t=2N) = \chi_N = H \sum_{j=1}^6 \sum_{n=1}^N Q_{n,j} G_{N-n+1, j} \quad (10)$$

where the summation over  $j$  includes all six power plants.  $N$  will be less than 50 since the maximum duration of hypothesized pollution incidents will be 4 days. Furthermore one can assume  $G_L = 0$  for  $L > 20$ .

Schematically this sum for  $t = 12$  hours ( $N=6$ ) from the start of the problem is

$$\chi(t=12) = \chi_6 = \left\{ Q_1 G_6 + Q_2 G_5 + \dots + Q_6 G_1 \right\} H$$

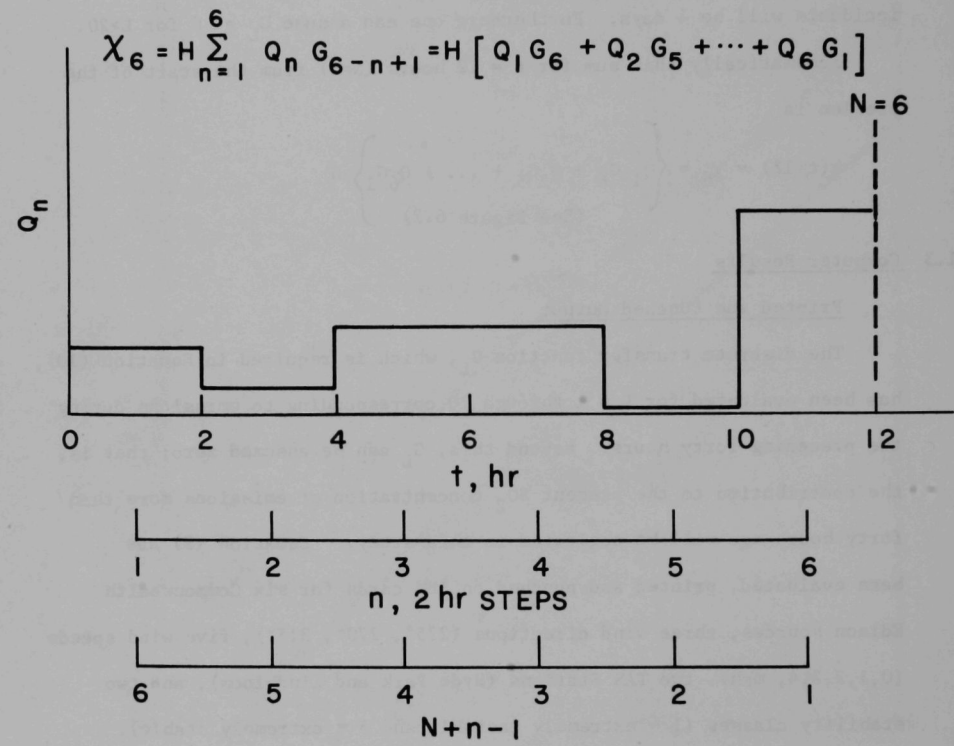
(See Figure 6.2)

### 6.1.3 Computer Results

#### Printed and Punched Output

The discrete transfer function  $G_L$ , which is required in Equation (10), has been evaluated for  $L = 1$  through 20 corresponding to emissions during the preceding forty hours. Beyond this,  $G_L$  can be assumed zero; that is, the contribution to the present  $SO_2$  concentration of emissions more than forty hours ago will be neglected in this study. Equation (9) has been evaluated, printed and punched on IBM cards for six Commonwealth Edison sources, three wind directions ( $225^\circ$ ,  $270^\circ$ ,  $315^\circ$ ), five wind speeds (0,1,2,3,4, mph), two TAM Stations (Hyde Park and Lindbloom), and two stability classes (1 = extremely unstable and 5 = extremely stable).

Users of this information will be provided with a complete listing of the associated arrays as well as punched cards. Each card has the source



112-9731

Fig. 6.2 Graphical Representation of the Application of the Discrete Transfer Function

identified in Column 6\*, the wind direction in columns 9-11, the wind speed in column 16, the TAM Station and stability class (HP1, L1, HP5, L5) in columns 72-76 as well as sequential numbering from 1-360 in column 77-80. The associated  $G_L$  arrays,  $L = 1, 20$ , appear sequentially in a 5E10.2 format beginning in Column 17. Note that the CDC-3600 at Argonne punches a number such as  $3.25 \times 10^5$  as 3.25+005, thus omitting the "E" of the traditional exponential format.

In addition to the printout of the  $G_L$  arrays, these values have been appropriately summed to indicate the buildup of  $SO_2$  following startup at time  $t = 0$ . This is printed at two hour intervals and should aid in the evaluation of the relative contributions of the six different sources under various conditions of wind direction, wind velocity and stability regimes.

This function is defined by

$$C_N = \sum_{L=1}^N G_L \text{ with } C_0 = 0. \quad (12)$$

Figures 6.3, 6.4, and 6.5 illustrate how program DAVKERN is used to "construct" a pollution incident for a single stack.

#### Comments on Numerical Results

The integration subroutine was verified to four place accuracy by evaluation of  $\int_0^\pi \sin x \, dx$ . The program DAVKERN was compared to the standard plume equation (4) modified by the assumption of constant mixing up to height  $z = H$ .

---

\*<sub>1</sub> = Northwest

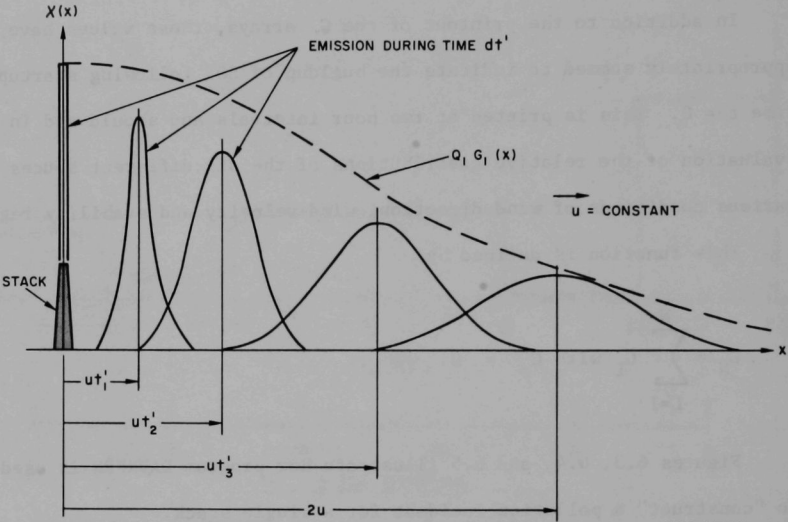
2 = Fisk

3 = Crawford

4 = Ridgeland

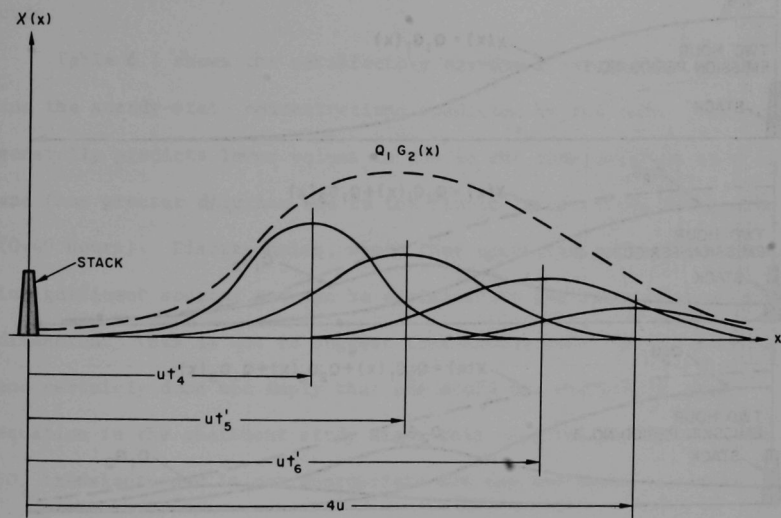
5 = Calumet

6 = Stateline



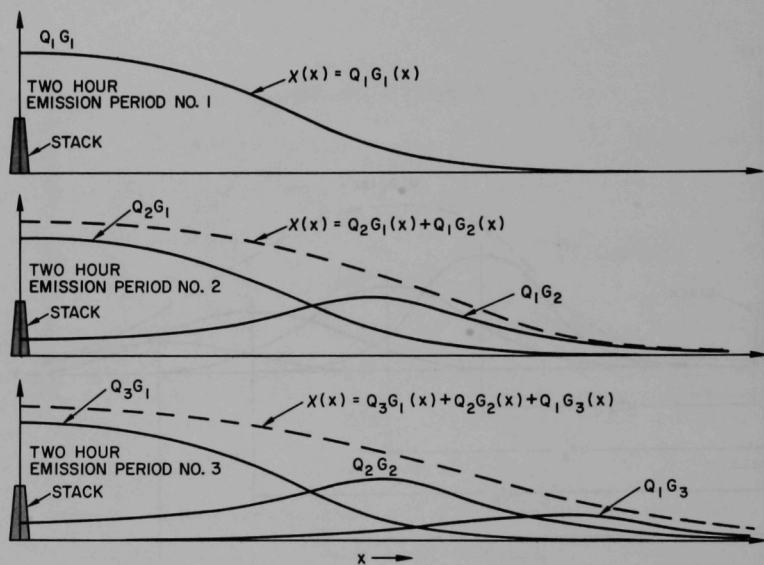
112-9732

Fig. 6.3  $\text{SO}_2$  Concentration During the First Two Hour Period of a Pollution incident Due to a Constant Emission  $Q_1$  During the First Two Hour Period of the Incident.



112-9733

Fig. 6.4  $SO_2$  Concentration During the Second Two Hour Period of a Pollution Incident Due to Constant Emission  $Q_1$  During the First Two Hour Period of the Incident



112-9734

Fig. 6.5 Build-up of  $SO_2$  as the Super Position of Consecutive Two Hour Releases.

$$\left( \frac{xH}{Q} \right)_{\text{Std. Plume}} = \frac{1}{(2\pi)^{1/2} u \sigma_y(t)} \exp - \left[ \frac{y^2}{2\sigma_y^2(t)} \right] \quad (13)$$

which can be evaluated directly for given  $u$ ,  $y$ , and  $t = x/u$ . This is

compared to steady-state concentrations  $C_{20} = \sum_{L=1}^{20} G_L$  calculated by the

code.

Table 6.1 shows the satisfactory agreement between the plume equation and the steady-state concentrations predicted by the code. That the code generally predicts lower values is due to the consideration of  $x$  dispersion and thus greater dilution and to the finite range of the integration (0-40 hours). Discrepancies, where they occur, are often for relatively insignificant sources and can be explained by the extra dispersion dimension. This is not to suggest that either model is the correct one and certainly does not imply that one could use the simple plume equation in the abatement study since this equation does not describe  $SO_2$  transients and is not appropriate for the  $u=0$  case.

TABLE 6.1

## PROGRAM DAVKERN vs. STD. PLUME EQUATION

Plant No.	WD/WS	TAM/STAB.	x	y	$\sigma$	$\frac{\chi H}{Q}$ Plume	$\frac{\chi H}{Q}$ Code
1							
Northwest	315/1	HP/5	11.75	4.0	3.6	.060	.059
Northwest	315/1	HP/1	11.75	4.0	10.5	.035	.028
2							
Fisk	315/1	HP/5	6.0	1.125	2.0	.171	.167
Fisk	315/1	HP/1	6.0	1.125	5.9	.066	.054
4							
Ridgeland	315/1	HP/5	8.88	5.38	2.8	.022	.030
Ridgeland	315/1	HP/1	8.88	5.38	7.3	.041	.028
5							
Calumet	315/1	HP/5	-4.75	2.0	-	0	$2 \times 10^{-5}$
1							
Northwest	315/4	HP/5	11.75	4.0	1.05	$3 \times 10^{-4}$	$1 \times 10^{-4}$
Northwest	315/4	HP/1	11.75	4.0	3.22	.057	.014
1							
Northwest	270/1	HP/5	5.5	11.12	1.8	0	$7.6 \times 10^{-4}$
2							
Fisk	270/1	HP/5	3.25	5.12	1.12	$4 \times 10^{-5}$	.005
3							
Crawford	270/1	HP/5	6.75	3.5	.220	.051	.058
4							
Ridgeland	270/1	HP/5	10.	2.5	3.20	.092	.090
5							
Calumet	270/1	HP/5	-2.0	4.75	-	0	$9 \times 10^{-5}$
1							
Northwest	270/4	HP/5	5.5	11.12	.54	$\sim 0$	$\sim 0$
Northwest	270/4	HP/1	5.5	11.12	1.72	$\sim 0$	$\sim 0$

## APPENDIX I

## Stack Data

## INDUSTRIAL STACK DATA

Bldg. No.	COMPANY NAME	NO. OF STACKS	STACK		TEMPERATURE
			HEIGHT	DIAMETER	
			feet-inches		
2	Campbell Soup Company	1	250'	12'	525° - 550°F
		2	175'	5' 5"	525° - 550°F
4	Sherwin-Williams Co.	1	180'	10'	450°F
6	International Harvester	1	204'		-
		3	100'		-
11	Darling & Company	1	61'	5' 6"	-
		1	90'	4'	-
		1	157'	10'	-
14	Crane Company	2	225'		-
17	International Harvester	1	120'		-
20	Darling & Company	1	280'	8'	-
22	Bird and Son	1	100'	4' 2"	-
24	Illinois Meat Company	1	150'	5'	-
25	American Can Company	1	210'	8'	-
29	Joanna Western	1	250'		-
32	Hammond Warehouse Co.	1	175'	12'	400°F
34	Hunt Wesson Foods (Wesson Oil & Snowdrift)	-	-	-	-
35	Rheem Manufacturing Co.	2	180'		-
		4	50'		-
36	Rock-Ola Corporation				500°F (I)
38	National Biscuit Co.	4	92'	2' 5"	-
39	Western Felt Works	1	160'	12'	-

INDUSTRIAL STACK DATA (contd.)

Bldg. No.	COMPANY NAME	NO. OF STACKS	STACK		TEMPERATURE
			HEIGHT	DIAMETER	
			feet-inches		
40	Superior Tanning Co.	1	103'	3'	450°F - 550°F
41	Standard Brands Company	1	138'		-
44	General Rendering Co.	-	-		-
45	Silver Cup Bakers (Gordon Baking Company)	1	150'		-
46	Cuneo Press Company	1	140'		-
50	Chicago Rawhide Mfg. Co.	1	135'		-
51	Chicago Sanitary District	4	175'	14' 10"	300°F - 350°F
52	Western Electric Company	1	250'	12'	-
56	Ward Baking Company	1	125'	5'	-

RESIDENTIAL STACK DATA

BLDG. NO.	COMPANY NAME	NO. OF STACKS	STACK		TEMPERATURE
			HEIGHT	DIAMETER	
			feet-inches		
<u>Chicago Housing Authority</u>					
a)	Taylor Homes	3	112'	3' 6"	400°F - 550°F
b)	ABYA Apartments	1	180'		-
		1	190'		-
c)	Cabrini Homes	9	40'	2'	350°F - 400°F
d)	Trumbull Apartments	-	-	-	-
e)	Stateway Garden Apts.	1	150'	6'	550°F
f)	Ickes Homes	1	80'	4'	550°F
		1	120'	3'	550°F
g)	Wentworth Apartments	1	120'	5'	-
h)	Lathrop Homes	1	103'		-
i)	Rockwell Apartments	-	-	-	-
j)	Murray Homes	-	-	-	-
k)	Henry Horner Apartments	1	150'	5'	330°F - 450°F
l)	Old Town Apartments	1	130'	4'	-
m)	Brockton Tower Apts.	-	-	-	-

COMMERCIAL STACK DATA

BLDG. NO.	COMPANY NAME	NO. OF STACKS	STACK		TEMPERATURE
			HEIGHT	DIAMETER	
			feet-inches		
a)	Tribune Square	-	-	-	-
b)	Merchandise Mart	1	380'	-	-
c)	Union Station	2	110'	-	-
d)	Cook County Hospital	-	-	-	-
e)	University of Chicago Blackstone Avenue Power Plant	2	159'	5' 5"	300°F - 550°F
f)	Illinois Inst. of Tech.	1	200'	6'	280°F - 400°F
g)	Prudential Building	1	675'	-	-



## SULFUR DIOXIDE EMISSION INDEX

AND

## METEOROLOGICAL NETWORK

for

## CITY OF CHICAGO AIR POLLUTION SOURCE INVENTORY

## Appendix II

INDUSTRIAL SO<sub>2</sub> SOURCES

Bldg. No.	Sq. Mile	Pgrm. No.	Program Coordinates		Company Name	Address
			X	Y		
1	2601	101	0.9	-12.0	Marblehead Lime Co.	3245 E. 103rd Street
2	0809	102	8.2	- 3.5	Campbell Soup Co.	2550 W. 35th Street
3	0307	103	6.5	+ 2.0	Procter & Gamble Mfg. Co.	1232 W. North Avenue
4	2805	104	4.1	-13.6	The Sherwin Williams Co.	11541 S. Champlain
5	3406	105	5.1	-16.0	Interlake Steel Co.	13500 S. Perry Avenue
6	0609	106	8.2	- 2.3	International Harvester	2600 W. 31st Blvd.
7	0105	107	4.5	+ 0.5	Container Corp. of America	404 E. North Water St.
8	2201	108	0.7	-10.2	United States Steel Corp.	3426 E. 89th Street
9	2602	109	1.5	-12.4	International Harvester Co.	2800 E. 106th Street
10	0512	110	11.4	+ 2.3	Central Soya Co.	1825 N. Laramie
11	1007	111	6.7	- 4.9	Darling & Co.	1251 W. 46th Street
12	2802	112	1.5	-13.1	Interlake Iron Corp.	11236 Torrence Ave.
13	2802	113	1.0	-13.1	Republic Steel Co.	11600 S. Burley Ave.
14	1010	114	9.0	- 4.3	Crane Company	4100 S. Kedzie Avenue
16	1013	116	12.4	- 4.0	Metropolitan Sanitary District	5901 W. Pershing Rd.
17	3007	117	6.3	-14.2	International Harvester Co.	1015 W. 120th Street
18	0708	118	7.9	+ 3.3	The Glidden Co.	2333 W. Logan

INDUSTRIAL SO<sub>2</sub> SOURCES (contd)

Bldg. No.	Sq. Mile	Pgrm. No.	Program Coordinates		Company Name	Address
			X	Y		
19	0105	119	4.7	+ 0.5	Wm. Wrigley Jr. Co.	410 N. Michigan Ave.
20	1008	120	7.0	- 4.4	Darling & Company	4210 S. Ashland Ave.
21	0307	121	6.2	+ 1.1	Container Corp.	900 N. Ogden
22	3002	122	1.6	-14.9	Bird & Son	2648 E. 126th Street
23	0111	123	10.8	+ 0.5	E. J. Brach & Sons	4656 W. Kinzie St.
24	1006	124	5.7	- 4.1	Illinois Meat Co.	3939 S. Wallace Ave.
25	1408	125	7.9	- 6.7	American Can Co.	6017 S. Western
26	0105	126	4.6	+ 0.7	Tribune Company	435 N. Michigan
27	0213	127	12.1	- 0.8	General Electric (Hot Point)	5600 W. Taylor
28	0507	128	7.0	+ 2.5	Horween Leather	2015 Elston Avenue
29	0406	129	5.9	- 1.9	Joanna Western	Cermack & Jefferson
30	3402	130	1.6	-16.1	United States Steel Corp.	13535 S. Torrence
31	0910	131	9.2	+ 4.4	Arvey Corp. Delaware Iron Co. Div.	3500 N. Kimball
32	1007	132	6.5	- 4.9	Hammond Warehouse Co.	4551 S. Racine
33	2802	133	1.4	-13.4	Great Lakes Carbon	2701 E. 114th Street
34	0811	134	10.6	- 3.1	Wesson Oil & Snow Drift	4421 W. 31st Street
35	1810	135	9.1	- 8.6	Rheem Mfg. Co.	7600 S. Kedzie
36	0310	136	9.0	+ 1.0	Rock-Ola-Corp.	810 N. Kedzie
37	0311	137	10.9	+ 1.5	Pettibone- Mulliken Corp.	4710 W. Division
38	0810	138	9.1	- 8.2	National Biscuit Co.	7300 S. Kedzie

INDUSTRIAL SO<sub>2</sub> SOURCES (contd).

Bldg. No.	Sq. Mile	Pgrm. No.	Program Coordinates		Company Name	Address
			X	Y		
39	0611	139	10.1	- 2.2	Western Felt Works	4115 Ogden Avenue
40	0307	140	6.5	+ 1.5	Superior Tanning Co.	1244 W. Division
41	1208	141	7.9	- 5.2	Standard Brands	4801 S. Oakley
43	0711	143	10.8	+ 3.6	W. F. Hall Printing Co.	4600 Diversey Ave.
44	1008	144	7.0	- 4.3	General Rendering	4200 S. Hermitage
45	1206	145	5.1	- 5.8	Gordon Baking Co. (Silvercup)	5324 S. Federal
46	0606	146	5.8	- 2.1	The Cuneo Press Co.	Cermak Rd. & Canal St.
48	0609	148	8.2	- 2.2	Handy Button Machine Co.	2255 S. Rockwell
49	0205	149	4.9	- 0.8	American Oil Co.	910 S. Michigan
50	0307	150	6.6	+ 1.6	Chicago Rawhide Mfg. Co.	1301 N. Elston

RESIDENTIAL SO<sub>2</sub> SOURCES

Bldg. Ltr.	Sq. Mile	Pgrm. No.	Program Coordinates	Name	Address
---------------	-------------	--------------	------------------------	------	---------

CHICAGO HOUSING AUTHORITY BUILDINGS

			<u>X</u>	<u>Y</u>		
a	1206	401	5.1	- 5.1	Taylor Homes	4800 S. State Street
b	0207	402	6.6	- 0.7	Abya Apartments	1313 W. Arthington
c	0306	403	5.5	+ 1.4	Cabrini Homes	418 W. Oak Street
d	2602	404	1.9	-12.4	Trumbull Apts.	2437 E. 106th St.
e	0806	405	5.0	- 3.7	Stateway Apts.	3640 S. State
f	0606	406	5.1	- 2.4	Ickes Homes	2400 S. Federal
g	0806	407	5.1	- 3.7	Wentworth Apts.	3700 S. Wentworth
h	0708	408	7.5	+ 3.5	Lathrop Homes	2000 W. Diversey
i	0209	409	8.1	- 0.5	Rockwell Apts.	2500 W. Harrison
j	3204	410	3.7	-15.8	Murray Homes	940 E. 132nd Street
k	0108	411	7.3	+ 0.2	Horner No. 2 Pt.	1834 W. Washington Blvd.

BUILDINGS NOT CHICAGO HOUSING AUTHORITY

l	0306	412	5.5	+ 1.9	Old Town Garden	1448 N. Sedgwick
m	1507	413	6.1	+ 7.1	Brockton Tower Apts.	5630 N. Sheridan

UTILITY COMMONWEALTH EDISON SO<sub>2</sub> SOURCES

nt .	Sq. Mile	Pgrm. No.	Program Coordinates		Name	Address
			<u>x</u>	<u>y</u>		
I	0909	201	8.5	+ 4.2	Northwest	3400 W. California
I	0407	202	6.4	- 1.9	Fisk	1111 W. Cermak
I	0810	203	9.9	- 3.5	Crawford	3501 S. Pulaski
V	1013	204	13.0	- 4.5	Ridgeland	4300 S. Ridgeland
V	2402	205	1.0	-11.6	Calumet	3200 E. 100th Street
I	2401	206	0.0	-11.9	State Line	103rd & Lake Streets

COMMERCIAL SO<sub>2</sub> SOURCES

g. o.	Sq. Mile	Pgrm. No.	Program Coordinates		Building Name	Address
			<u>x</u>	<u>y</u>		
	0105	501	4.6	+ 0.8	Tribune Square	435 N. Michigan
	0106	502	5.4	+ 0.5	Merchandise Mart	Merchandise Plaza
	0206	503	5.6	- 0.3	Union Station	301 W. Taylor
	0208	504	7.3	- 0.5	Cook County Hospital	1835 W. Harrison
	1404	505	3.5	- 6.4	University of Chicago	6101 S. Blackstone
	0806	506	5.2	- 3.2	Ill. Institute of Technology	3300 S. Federal

## METEOROLOGICAL NETWORK

Pyrheliometer

No.	Sq. Mile	Pgrm. No.	Program Coordinates		Site	Address
			<u>x</u>	<u>y</u>		
1	0206	701	5.6	- 0.9	Chicago Fire Academy	550 W. Dekoven

Hygrothermograph (7 Day)

2	0405	601	3.8	- 1.3	Merrill C. Meigs Field	Outer Dr. at 14th St.
3	0606	602	5.1	- 2.7	Daniel Hale Williams Elementary School	2710 S. Dearborn St.
4	0807	603	6.2	- 3.4	Philip D. Armour Elementary School	950 W. 33rd Place
5	0808	604	7.2	- 3.6	Nathanael Green Elementary School	3537 S. Paulina St.
6	1009	605	8.2	- 4.5	James Shields Elementary School	4250 S. Rockwell St.
7	1009	606	8.7	- 4.7	Frank W. Gunsaulus Elementary School	4420 S. Sacramento
8	1211	607	10.2	- 5.2	Richard Edwards Elementary School	4815 S. Karlov Ave.
9	1413	608	12.8	- 6.9	Hale Elementary School	6140 S. Melvina Ave.
10	2625	609	24.1	-12.8	Argonne National Laboratory	Argonne, Illinois
11	0106	610	5.1	+ 0.5	Central Office Bldg. City of Chicago	320 N. Clark Street

Aerovane

12	1513	301	12.8	+ 7.1	William Howard Taft High School	5625 N. Natoma Ave.
13	1107	302	7.0	+ 5.1	Lake View High School	4015 N. Ashland

## METEOROLOGICAL NETWORK

Aerovane (contd.)

Sq. Mile	Pgrm. No.	Program Coordinates		Site	Address
		<u>X</u>	<u>Y</u>		
0206	303	5.1	- 0.5	General Services Administration Building	536 S. Clark St.
1404	304	3.0	- 6.9	Hyde Park High School	6220 S. Stony Island
1408	305	7.4	- 6.8	Robert Lindblom High School	6130 S. Wolcott
2806	306	5.8	-13.1	Christian Fenger High School	11220 S. Wallace
0112	307	11.9	+ 0.2	Austin High School	231 N. Pine Ave.
2011	308	10.5	- 9.2	Adlai E. Stevenson Elementary School	8010 S. Kostner
0106	309	5.1	+ 0.1	Civic Center	Clark & Randolph Streets

## TELETYPE REPORTING STATIONS

Dare International Airport  
 Fenwick Naval Air Station  
 Highway Airport  
 Lags Field

## ACKNOWLEDGEMENTS

The authors of this report wish to express their gratitude to Messrs. Booras, Loquercio, Klappenbach, Murphy, Lin and Votruba of the Chicago Department of Air Pollution Control for their cooperation, advice and assistance in the acquisition of much of the data discussed in this document.

Thanks are due to Mr. D. J. Quinn of the Reactor Engineering Division of Argonne National Laboratory for assistance in the design of the building instrumentation experiment.

Thanks are also due to Mrs. M. Parrish, Miss H. Rihel and Miss L. English of the Reactor Engineering Division of Argonne National Laboratory for their assistance in the preparation of this report.

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